Design of an X-Y Table for Investigating And Rehabilitating Human Motor Control

Undergraduate Honors Thesis

By

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ABSTRACT

Approximately two million stroke survivors in the United States have chronic arm impairment. Despite increasing evidence that an injured human central nervous system (CNS) can reorganize itself with motor practice, patients today are receiving less therapy following a stroke. Robotic therapy devices can provide for lower-cost therapy that would permit the level of motor practice necessary to regain arm function. The proposed research project seeks to design, build, and test a powered X-Y table capable of applying force fields for human CNS studies. The goal is to develop an X-Y table that is capable of applying more effective force fields than existing robotic devices. Initial experiments will be conducted in order to validate that the X-Y table functions as designed and is capable of applying the desired force fields required for the investigation of the human CNS. Once the X-Y table effectiveness has been verified, the system will later be used in tests designed to validate existing kinematic and dynamic models.

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CHAPTER 1 - INTRODUCTION

Background

Approximately two million stroke survivors in the United States have chronic arm impairment [3]. With baby-boomers soon reaching the age of 55, where stroke incidence doubles for every subsequent decade, the number of disabled stroke survivors will undoubtedly increase [4]. The rehabilitation process for these individuals is extremely labor-intensive, relying on numerous hours of therapy [4]. Robotic therapy devices can supplement that labor-intensive, one-on-one therapy that would in turn, enable the level of motor practice necessary to regain arm function. The increased understanding of human motor coordination gained from these devices will possibly lead to the development of better clinical therapy processes that improve post-injury recovery. A better understanding of human motor coordination can lead to a more accurate model of the human central nervous system (CNS). Along with facilitating therapy, these devices can provide a means of quantitatively measuring a victim's impairment along with their relative improvements. This thesis discusses the development of an X-Y table designed for experiments to prove that the foundational model employed for motor coordination may be based on geometric kinematics rather than dynamics. The models obtained from this project can be used in conjunction with devices designed for diagnosing and treating motor coordination problems to better care for individuals who suffer from chronic arm impairment caused by stroke.

Motivation

Individuals who suffer strokes have the possibility of suffering from upper limb impairments if the brain is damaged. Reaching tasks may become difficult or impossible for the victim to complete following a stroke. It has been seen that these reaching tasks require the central nervous system (CNS) to solve the inverse kinematic problem for the arm [10]. Straight-line hand paths [11] and fixed relations between the elbow and shoulder angles [7] are evidence that adaptation of movement is driven by a time invariant plan. Additional evidence includes hand path shape in reaching movements being independent of trajectory speed [10, 11]. This behavior suggests that the fundamental internal model used for motor coordination may be driven by kinematics rather than dynamics. If dynamics is the driving force behind the internal model, movement adaptation would optimize dynamic characteristics including power, joint torque or muscle force [12,14]. Both kinematic and dynamic criteria may have a large influence on motor adaptation to an applied force field [9]. It was seen, thought, kinematic dependent factors play a dominant role in rapid loss of adaptation after the restoring of the original dynamics [9].

Clinical testing using a device known as the MIT-MANUS shed a great deal of light on robot-assisted rehabilitation. The primary purpose of the device was to determine if exercise therapy influenced the recovery of the brain following stroke. The MIT-MANUS is a 2-degee-of-freedom (DOF) planar device that uses low inertia motors to directly drive the 5-bar linkage design. The MIT-Manus is capable of moving, guiding, and perturbing a subject's upper limb. While performing these routines, the device is able to record mechanical quantities such as position, velocity, and force applied to the subject's upper limb [5]. The outcome of the testing revealed that robot-aided therapy does not have any adverse effects and is well tolerated among the patients. Also, manipulation of the impaired limb may influence brain recovery following neurological injury [4].

Studies using the Mirror Image Motion Enabler (MIME) validated the feasibility of quantifying interaction forces during mechanically assisted upper limb movements [2]. Additional advantages in terms of clinical and biomedical measures using robot-assisted movements were also identified [6]. The MIME is a 2-DOF forearm-elbow-arm exoskeletal orthosis capable of operating in a master/slave configuration. The upper limbs can be moved in either a reciprocal or mirror image pattern. While operating in the reciprocal pattern, the contra-lateral limb determines the desired motion for the paretic arm by completing the desired motion first. When the MIME is operating in the mirror image pattern, the paretic limb's movement will directly follow the contra-lateral limb's motion at the same instant in time, but in a mirrored fashion [2].

The Assisted Rehabilitation and Measurement (ARM) Guide was designed to prove that rehabilitators can produce quantifiable benefits in paretic arm rehabilitation. As a diagnostic tool, the ARM Guide could be used for assessing the impairment of arm movement following brain injury, while the effects of active assist therapy could be explored when the device was used as a therapeutic tool. Abnormal tone, spasticity, and incoordination were the motor impairments identified and evaluated with the ARM Guide. It was determined through clinical testing that increased tone along with agonist weakness were impairments that limited arm movement. Incoordination, which is characterized as a lack of directional force control, was also identified as an impairment that limits arm motion. The most important result from the ARM Guide is that active assist therapy using robot-rehabilitators can produce quantifiable benefits [8].

The previous projects contributed tremendously to the robot-assisted rehabilitation, but many limitations can be identified. One is design of the test apparatuses. In the case of the MIT-MANUS, variable apparent endpoint inertia was always present due to the design. This and other similar robots based on the 5-bar linkage always have this problem, forcing them to operate at lower speeds with smaller amounts of force feedback. Because the MIT-MANUS is a 5-bar mechanism, different motion patterns require motion of different sets of links at different times in the motion profile. If all five links are required to complete a motion, a different amount of force will be required to change the momentum of the links, while if only one of the links is required for the desired motion, a smaller force will be required to change its momentum. The robot also operates in a smaller workspace to compensate for the varying inertia. In order to operate in a larger workspace, larger links would be required, but these larger links would have a larger mass and cause a higher variation in the apparent endpoint inertia.

Figure 1 is an illustration of varying apparent endpoint inertia. Schematic A shows that as the motion is confined to rotating about the revolute joint connecting links 1 and 2, link 2 does not move and the inertia remains constant throughout the motion sequence. Schematic B shows that for other motions requiring both links 1 and 2 to move, the apparent endpoint inertia is no longer constant.

A new approach was employed in the design of the X-Y table to provide constant apparent endpoint inertia throughout the entire workspace of the device. Locating the table's drive motors outside the system allowed for a design that had nearly constant apparent endpoint inertia. Timing belts and timing belt pulleys were employed as a means of driving the table because the motors were mounted external to the system. The X-Y table is a prismatic-prismatic (PP), 2-DOF kinematic mechanism. Other 2-DOF kinematic systems include the revolute-prismatic (RP), revolute-revolute (RR), and prismatic-revolute (PR). The naming conventions for each are composed of the type of joints present. The first joint in the naming convention is connected to ground, and the second is connected to the link extending from ground. Figure 2 is an illustration of the four possible 2-DOF open chain systems composed of lower-pair joints.

Figure 1 - Varying Inertia Illustration [15]

There are other similar planar tables in use, the main differences being in the intended purposes. None of the existing planar tables were designed for the use in motor coordination studies or robot-assisted rehabilitation. A haptic device known as the Linear Haptic Display (LHD) was designed and tested in the BioRobtics Laboratory at the University of Washington. The LHD is a 3-DOF haptic device designed to use a moderate workspace, while implementing large forces and maintaining a high structural stiffness [1]. The device uses a 12”x 12” planar active workspace and has external dimensions of 27” x 27” for the entire device. The LHD is capable of achieving a maximum continuous force of 22.5 lbf and a maximum peak force of 45 lbf. With a 32” x 28.75” workspace, the X-Y table presented in this thesis has a considerably larger workspace. With both devices being either belt/chain driven along low-friction linear rails, there is tremendous promise that the X-Y table will work properly.

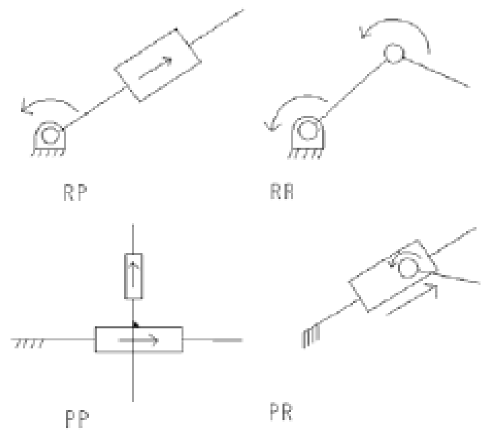


Figure 2 - 2-D Kinematic Machine Representations [13]

CHAPTER 2 – HARDWARE DESIGN / COMPONENT SELECTION

The robot design process was started once the system requirements had been determined. Requirements included little to no variance in apparent endpoint inertia along with the ability to apply a force up to 40 lbf to a subject's arm. The process involved determining which components needed to be purchased, purchasing the necessary parts, and designing parts that could not be purchased off-the-shelf. The completed machine is shown in Figure 3, and a complete parts list for the device can be found in the Appendix.

Figure 3 - Completed X-Y Table

Overall Machine Design

The X-Y table uses a handle attached to the crossbar bearing housing the user interface. The handle is interchangeable through use of a mounting bracket and can be replaced with different handle shapes. The crossbar bearing housing and the handle are designed to slide along two hollow cross shafts that ride on bearings. The cross shafts are hollow to minimize the inertia of the system. Each shaft is attached to a crossbar housing that clamps a timing belt in between it and a linear pillow block. This linear pillow block slides along a rail that traverses the entire length of available workspace. Each timing belt is connected to a set of pulleys. Four of the pulleys are attached to the motor drive shafts, while the remaining four pulleys are attached to the shafts that aren't connected to the motors. Motion is accomplished along each axis through the motor turning the coupled drive shaft, which in turn rotates the pulleys that drive the timing belts. Since each crossbar is indirectly attached to the timing belts, the shafts will move in the desired direction.

A goal for the X-Y table was to have a large useable workspace throughout which the apparent endpoint inertia remained constant. Originally it was desired to design a table that had a 36” x 36” square workspace for a wide range of force field adaptation experiments. Further consideration suggested that a rectangular table would be better suited for the test subjects’ positioning and reaching patterns. If a subject is oriented in the middle of the table and his/her arm is of length L, that subject has the ability to reach L to his/her left and L to his/her right. This results in a total lateral reaching length of 2L. In the case of the subject reaching directly out in front of himself/herself, he/she only has the ability to reach a distance of L. With this in mind, a rectangular available workspace of 32” x 28.75” was selected. The available workspace length and width were both decreased from the original dimensions because only a small percentage of the population would be able to utilize a workspace that large. The 32” in width is adequate for the majority of the population, while the 28.75” in length is more than enough length to accommodate all arm lengths. In order to maintain constant apparent endpoint inertia, it was necessary to keep the table as close to square as possible.

Selected Hardware

The off-the-shelf items were identified first because the rest of the device was designed around the constraints the selected hardware placed on the system. The hardware that included linear bearings, motors, timing belts, pulleys, a load cell, and control electronics.

Linear Bearings

Once the overall X-Y table had been determined, it was necessary to devise a method of actually driving the crossbars. Several linear motion options were considered, but a Thomson low profile linear rail and linear bearing system was selected because of the low coefficient of friction and relative ease of integration. The rail and bearing combination provided coefficients of friction as low as 0.001. The rails were attached to the base of the system, and ball bushing pillow blocks were slid onto the rails. Machined crossbar housings were then attached to the ball bushing pillow blocks, and Thomson tubular shafting was fixed in the crossbar housings. The

Thomson tubular shafting was chosen hollow to reduce weight and inertia. The assembly is shown in Figure 4.

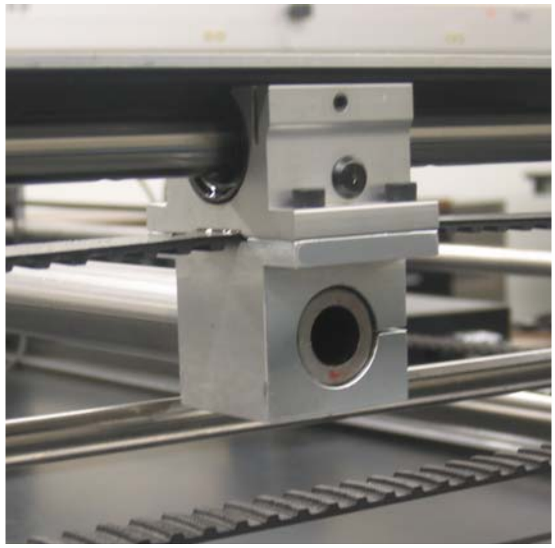


Figure 4 - Low Profile Rails, Pillow Block, & Crossbar Housing Assembly

Motors

The motors for the X-Y table had provide high torques while having low inertia for back-drivability. Without the option of using a gear-head to produce additional torque, only high-torque motors could be considered. The Emoteq HT03004 was selected from their high torque series of brushless DC motors that provide high torque-to-inertia and size ratios. It has an operating voltage of 24 V. The Emoteq HT03004 is capable of providing a maximum torque of 8.85 ft-lbf. With a pulley attached to the motor shaft that has a pitch diameter of 2.387", the X-Y table is capable of producing a maximum peak force of 44.5 lbf.

Along with an adequate motor to drive the system, an encoder was needed to sense the motor position. The encoder packaged with the motors was a 1000 count unit with quadrature. Conversions from encoder counts to position can be found in a later section..

Timing Belts / Pulleys

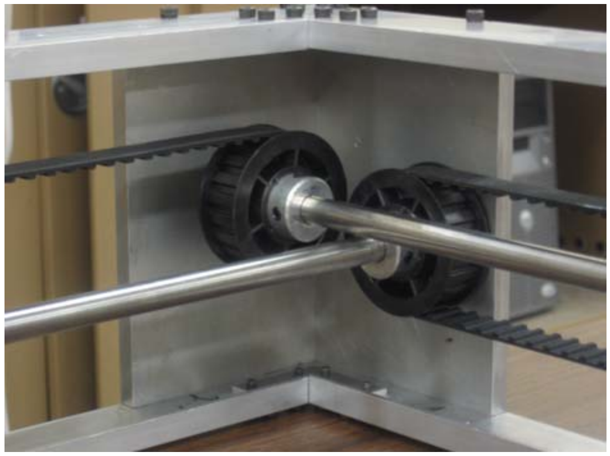


Figure 5 - Motor Drive Shaft Timing Belt Drive System

Because the motors had to be mounted external to the the table, a method to generate the desired motion patterns had to be determined. The best solution for this was to use timing belts and timing belt pulleys attached to the two motor drive shafts. Each of the two motor drive shafts had two timing belt pulleys located on it that would drive the timing belt and in turn, the timing belt pulleys located on the opposing non-motor drive shafts. Figure 5 is a picture of the timing belt drive system is taken from within the X-Y table.

The X-Y table utilizes a trapezoidal tooth profile timing belt from the Gates Corporation known as the PowerGrip®. Based on a pulley rotational speed of 6000 rpm the PowerGrip belt is capable of transmitting torques in excess of 40 in-lbf. The trapezoidal tooth profile is an older style of timing belt. More recently, Gates has developed a high-torque PowerGripGT2® line of belts that utilize a more rounded tooth profile. The PowerGripGT2 belts of similar width are capable of transmitting 164 in-lbf of torque. It was decided that the added torque capabilities did not warrant the extra cost of these belts. With the trapezoidal tooth profile, type L belts or larger were required for the expected loads, and the largest width, ¾", was selected for load carrying capability.

The pulley was selected based on the available size within the X-Y table and the belt. The pulley had to be small enough to allow for clearance between the top and bottom base rails along with not interfering with the drive shafts, but still large enough to engage enough timing belt teeth. If too few teeth are engaged, slip may occur at higher torques. A pulley with a diameter of 2.387" that accepted ¾" type L timing belts was chosen because of its adequate load carrying capabilities and fairly compact size.

Since a 1:1 drive ratio was desired between each set of pulleys, calculation of the center distances for the pulleys was fairly simple. The X-Y table's workspace and dimensions were set by the standard pitch lengths available for the timing belts. The total timing belt length, L_{belt}, was governed by Equation 1, where D_p is the pulley pitch diameter and CD is the center distance between the pulleys.

Equation 1

$$L_{belt} = \pi D_p + 2CD$$

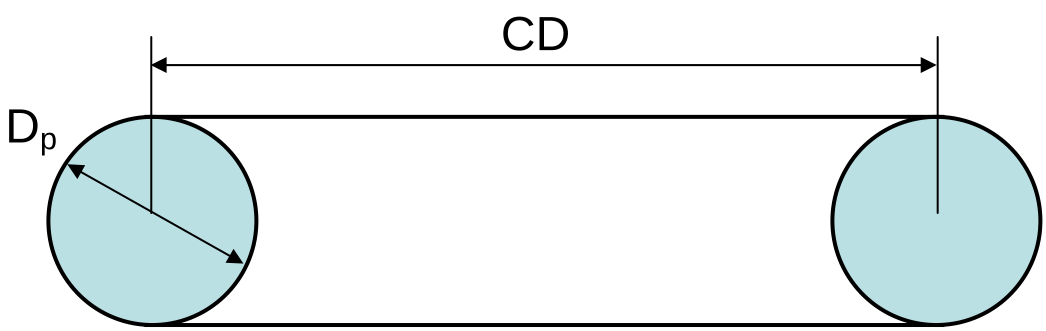


Figure 6 – Belt Length Illustration

Figure 6 is an illustration of how the belt length is parameterized. The equation for the belt length is simply the sum of half of each pulley's circumference and two times the center distance. Belt lengths of 78" for the long side and 72" short side were identified for the X-Y table, corresponding to center distances of 35.25" and 32.25", respectively.

Control System

In order to operate the motors, a control card, amplifier, and power supply had to be selected. These three components combined to form the control system for the table. The control card received a command from the user and sent a signal to the amplifiers. The amplifier then amplified that signal to an acceptable power level and sent that to the motors. The power supply converts the 120V AC from the wall outlet to DC to drive the brushless DC motors.

The control card was selected first. The control card acted as the language translator for the entire system. A user would input a desired condition to the control card, and the card would translate and send the appropriate signal to the remainder of the control system. To allow for simplified installation, only control cards that interfaced with the PCI bus ports located in the back of the PC were considered. Because all desktop PCs come with this port, it would eliminate the need to purchase a special computer system solely devoted to the operation of the X-Y table. Another advantage is that no external power supply has to be provided to power the card because it will pull power directly from the computer. The second requirement was that the control card had to be multi-axis to operate both axes of motion. The control card identified was the DMC-1820 from Galil Motion Control, capable of independently controlling four axes thereby allowing for system expandability. The DMC-1820 is configurable for either stepper motors or servomotors and the appropriate encoders for each. The control card comes with its own programming language that can be used as a stand-alone operating system or configured to operate with Visual Basic or C programming languages to create a unique graphical user interface (GUI). An additional interconnect module was purchased to cleanly connect the large number of wires coming from the X-Y table to the control card.

Following selection of the control card, a pair of amplifiers could now be selected to amplify the power sent to the two drive motors. The selection of the amplifiers was relatively simple because the brushless DC motors with rated peak amperage of 19.1 A and voltage of 24 V had already been selected. The selected amplifier was the Advanced Motion Controls model BE30A8 with a DC supply voltage range of 20-80V and a maximum continuous current of 15 A.

The power supply was the final aspect of the control system selected. With a motor operating voltage of 24 V and an amplifier peak current of 30 A, the maximum power each motor/amplifier combination could use would be 720 W. Since the peak current could only be used for a short period of time, the maximum continuous current of 15 A yielded a power output of 360 W. (Each motors rated continuous output power was 200 W.) It was desired to operate both motors off of the same power supply, requiring a single unit capable of delivering 720 W of continuous power. The 800 W PS16L30 was from Advanced Motion Controls.

Wiring the control system was a somewhat complicated task. The system utilized several wires and connection ports for each component. The interconnect module provided 100 available connection ports, while each amplifier had 21 available ports. Each motor contained eight output wires, with each accompanying encoder providing an addition five wires. Because the majority of the connection ports within the interconnect module were unused, adequate and accurate documentation had to be written to ensure correct connection. The wiring diagram for each motor is located in the Appendix. The complete wiring of the control system required connecting the power supply, motors, and interconnect module to the amplifier while also properly connecting the motor encoders to the interconnect module. The amplifiers required two ribbons. One was a 16 pin ribbon that interfaced with both the motor and interconnect module, while the motor and power supply interfaced with a 5 pin ribbon. Once properly wired, the ribbon allowed for easy connection and disconnection of the amplifier. The motor armatures needed to be connected in the correct order for the motors to operate properly. If improperly connected, the motors could operate in the wrong direction, run hot, or function in a jerky fashion. The white, black, and red wires corresponded to armatures A, B, and C, respectively, on the motor. The wires representing the A, B, and C armatures on the motor were connected to the A, B, and C connection ports located on the amplifier.

Force Sensing

For testing with the X-Y table involving force sensing, a method of measuring forces applied by the user had to be devised. A 6-DOF load cell was determined to be an adequate method of force measurement. The load cell would have to be compactly packaged and easily interfaced with the existing crossbar bearing housing. Compactness of the load cell was desired because the height of the load cell directly related to the overall height of the handle. Excessive handle height would result in the subject conducting reaching exercises in an elevated and unnatural plane, possibly causing discomfort in the shoulder joint. The maximum load that the load cell would see from a healthy human subject was estimated to be 50 lbf. A load cell capable of accurate measurements at both high ranges near the maximum force and at low ranges well below the maximum force had to be selected. The Mini45 DAQ F/T transducer from ATI Industrial Automation was selected because of its compact, low-profile design. At only 0.62" in thickness and 1.77" in diameter, the Mini45 left enough room to give a more natural feel to the handle. This load cell came with the option of dual calibration: one for low payloads with a high resolution and one for larger payloads with a lower resolution. The higher resolution calibration is good for forces in the x and y-directions up to 30 lbf, and forces as high as 60 lbf in the z-direction. The higher range, lower resolution calibration, is able to operates with forces as high as 60 lbf in the x and y-directions and a force of 120 lbf in the z-direction. The DAQ F/T connects to the operating computer through the PCI port and comes with software that can be modified for the desired applications.

Designed Components & Assembly

The base rails, corner supports, crossbar bearing housings, crossbar housings, and motor mounts of the X-Y table had to be designed and. All of these components were machined from stock aluminum because it was deemed structurally strong enough for intended purposes. Along with aluminum providing great weight and cost savings over other potential materials, it was also non-magnetic. Eventually, magnetic sensors will be implemented with the system to measure arm orientations. If ferrous or other magnetic materials were used for the majority of the components, erratic operation may be experienced in the sensors.

Base Rail

The X-Y table consists of eight base rails, four for the top and four for the bottom. The base assembly consists of base legs 42.0” and 37.625” in overall length, as determined by the timing belt lengths. Two of the long legs and two of the short legs were drilled and tapped to allow for attachment of the Thomson low profile shaft rails, while the remaining legs were left unmodified because they were not intended to accept any additional hardware. Figure 7 is a rendered illustration of both the unmodified base leg and one that has been drilled and tapped. Each base leg was also designed with a 0.125” lip on the inner edge, initially intended to increase the structural rigidity of the system, but it was later removed to resolve interference issues. The lip removal caused no degradation in the rigidity of the system.

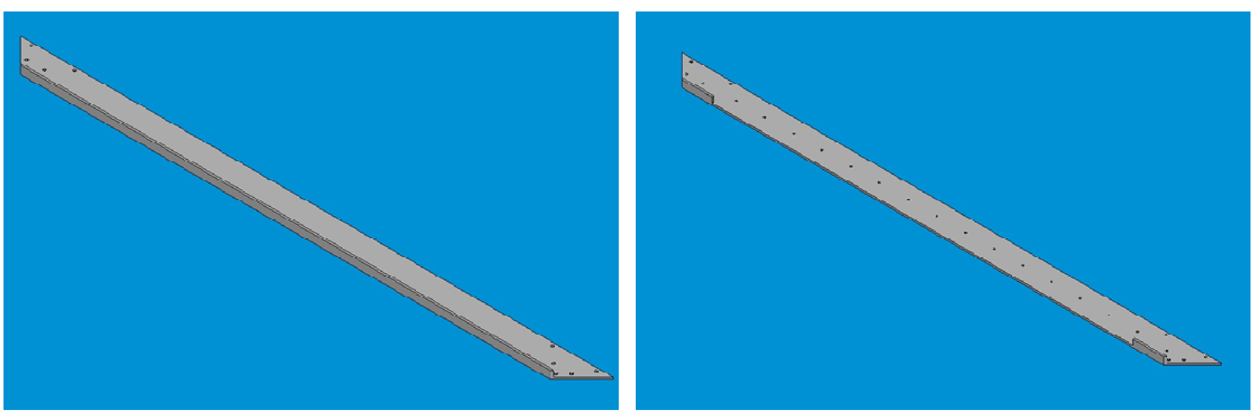


Figure 7 – Standard and Modified Base Leg

Corner Support

Eight corner supports were required for assembly of the X-Y table. Each corner support was machined with a recessed ball bearing housing. Of the eight corner supports, four were designed with the ability to add tension to the timing belt attached to the corresponding pulley since timing belts may stretch over time, a procedure to take up the created slack was needed. These corner supports provided 0.5" in travel for tensioning. Figure 8 shows one of the four corner supports with tensioning capability. The outer race of the ball bearing is allowed to travel within the ball bearing housing. Tightening the socket head cap screw forces the ball bearing deeper into the housing, and increased tension is produced. The ball bearing is press fit in each housing of the four corner supports without the tensioning device. It was advantageous to make the corner supports as short as possible since their height dictated the overall height of the X-Y table. The corner supports were designed to be 6.367", the minimum height that would allow the railing, pillow block, timing belt, and pulley of the X-Y table to properly stack up together.

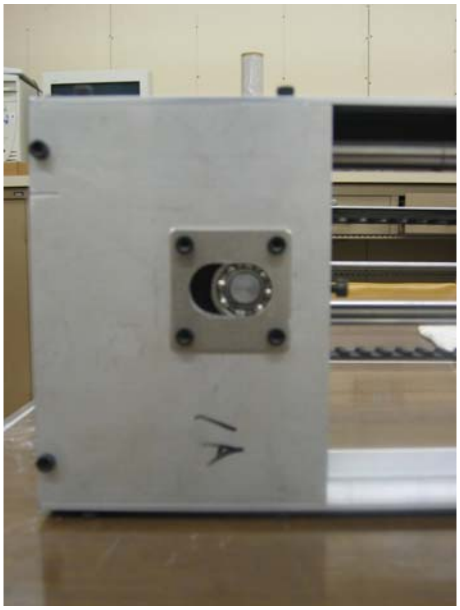


Figure 8 - Corner Support With Tensioning Capabilities

Crossbar Bearing Housing

Figure 9 depicts crossbar bearing housing, which serves two functions. The first is to coordinate the motion between the x-axis and the y-axis with ball bushing linear bearings through which the linear race tubular shafts pass. The second function is to affix the load cell and handle assembly to the rest of the system. Four holes were drilled and tapped in the top of the crossbar bearing housing to mount an adapter plate for the load cell and handle. The adapter plate was designed because the load cell was the last piece of hardware identified and purchased. With the size and bolt pattern of the load cell unknown for a large portion of the project and the crossbar bearing housing an integral part, an adapter plate was needed to interface the two components at a later time. Slits were cut into the top and bottom of the crossbar bearing housing in to allow for proper tightening of the linear bearings. Over tightening of the linear bearings results in stiff motion performance.

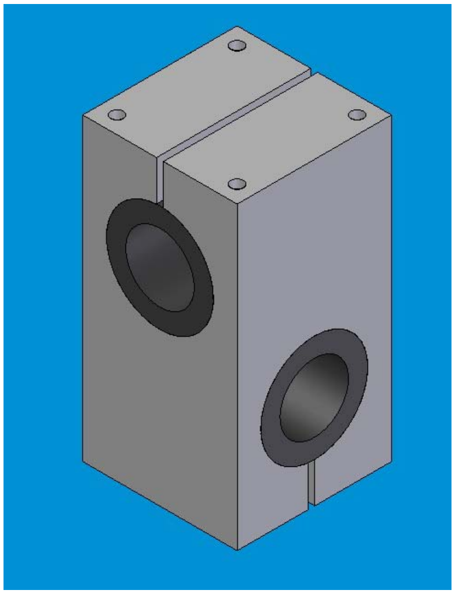


Figure 9 - Crossbar Bearing Housing

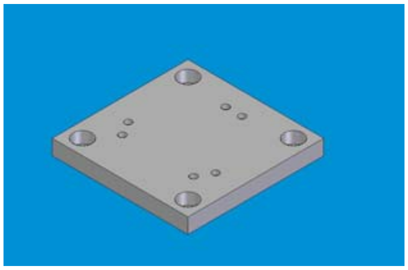


Figure 10 - Load Cell Adapter Plate

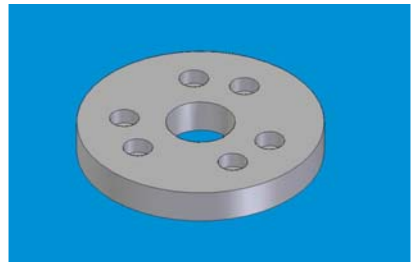


Figure 11 - Load Cell Top Plate

Because the load cell was the last item selected for the X-Y table, the crossbar bearing housing was designed with four #10 holes with the idea of an adapter plate being used to secure the load cell to the crossbar bearing housing. Figure 10 is a picture of the adapter plate. The plate is first fixed to the crossbar bearing housing with four #10 screws. The load cell is then placed on top of the plate and fixed to the plate with the appropriate screws. Figure 11 is a picture of the load cell top plate. This plate is used to securely connect the handle to the load cell. The top plate is first bolted to the load cell, and then the handle is screwed into the ½" internally threaded hole in the center of the plate. Figure 12 shows the complete subassembly of the load cell and handle, demonstrating just how small and unobtrusive the load cell is. The handle is elevated only a minor distance to accommodate the load cell.

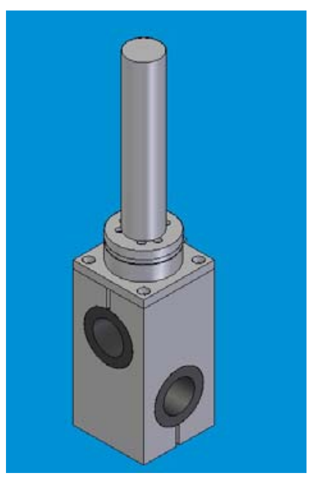


Figure 12 - Load Cell & Handle Assembly

Crossbar Housing

The crossbar housings were designed to accept the linear race tubular shafting on each of the four sides of the X-Y table. Motion from the timing belts would be transferred to the crossbar housing, and the crossbar housing would then transfer that motion to the shafting and crossbar bearing housing. Four crossbar housings were required, with each having five equally spaced grooves cut in the bottom to engage the timing belt teeth. By sandwiching the timing belt between the crossbar housing and the purchased Thomson linear race pillow block, the timing belt was fixed within the system. Figure 14 shows of the subassembly of the crossbar housing, pillow block, and timing belt.

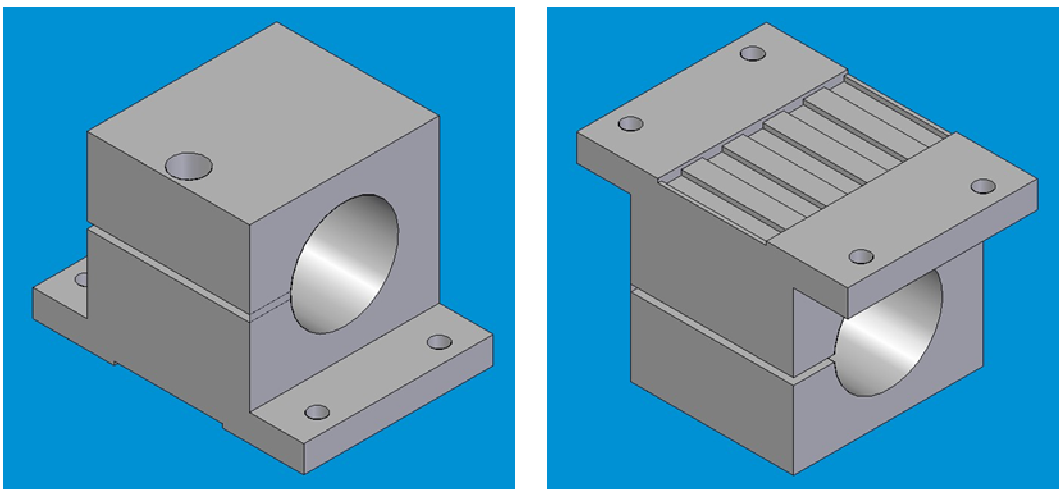


Figure 13 - Crossbar Housing

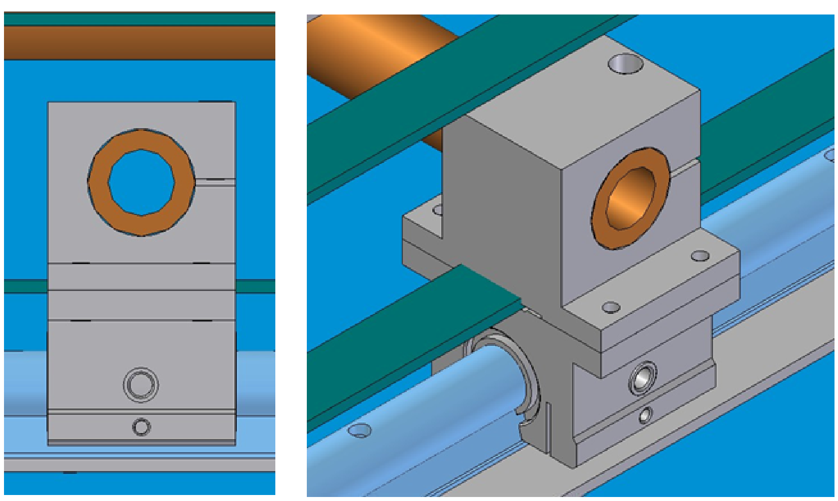


Figure 14 - Crossbar Housing & Pillow Block Subassembly

Motor Mount

Motor mounts were the final components manufactured for the X-Y table. The X-Y table is powered by two externally mounted motors. Although the drive system for the X-Y table was somewhat complicated, the hardware used to mount the motors was relatively simple. The motor mounts were designed to be 4” high and 3.5” wide. The relatively large size of the mounts was due to the large volume and weight (67.9oz.) of each high torque motor. The larger mounting area allowed for adequate bolting space. The motor mounts were designed to be 4” in depth. Originally it was desired to minimize the depth of each mount, but the depth was driven by the 2” length of the heavy duty flexible couplings used to attach the motor to the drive shaft. Figure 15 is a picture of the motor mounts with the flexible couplings attached to the drive shafts.

Assembly of the X-Y table was a somewhat involved task with several idiosyncrancies. The device had several components that could only be put assembled in certain orders. The table assembly instructions are located in the Appendix.

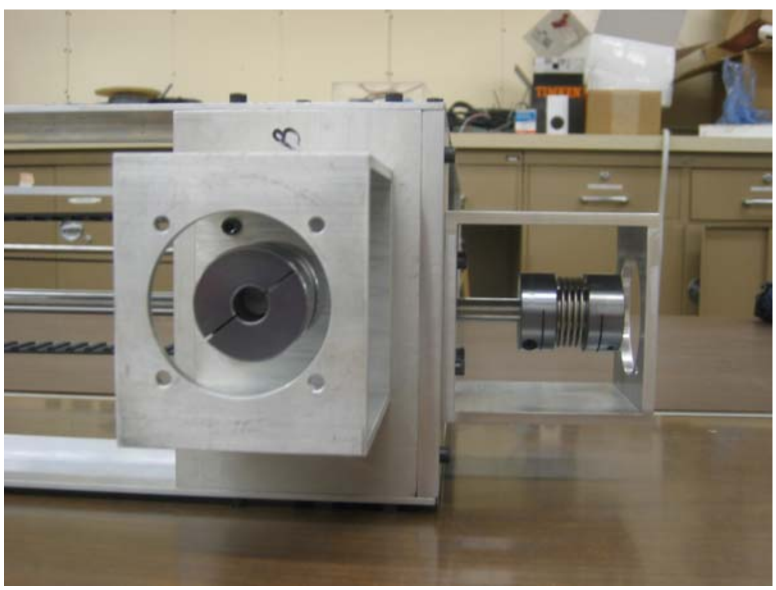


Figure 15 - Motor Mount and Motor

CHAPTER 3 – PROGRAMMING / SOFTWARE

Following the completion of the construction, assembly, and wiring of the X-Y table, the next task was programming motion. The programs written to generate motion for the X-Y table run directly from the control card. The language of the programs is specific to the control card. Three preliminary programs were written: the first traces the physical dimensions of the table, the second allows the user to specify a rectangle or a circle, and the third is a user-specified reaching program.

Galil Control Programs

Terminal software included with the control card was used to write, debug, and execute the motion programs. The first few programs designed were written and tested with the motors removed from the apparatus to prevent damage to the apparatus or the motors while familiarization with the software was established. Upon obtaining confidence with the software, the motors were reattached to the apparatus, and the more complicated programs were completed.

The motors used on the X-Y table had to be initially tuned (gains properly set) when they were integrated into the system. The motors were first detached from the system and individually tuned to become familiar with the process. When the motors were reattached to the system, they had to be retuned because of the added torque and changes in inertia encountered by connection to the drive shafts. The control card used a proportional-integral-derivative (PID) control scheme. Three gain values had to be set for each axis. These three gains were the proportional gain (KP), integral gain (KI), and derivative gain (KD). To determine the appropriate values for these gains, all three were set to their lowest allowable value. The proportional and derivative gains were then gradually and incrementally increased until the maximum values were obtained for the KD and KP without having any noticeable vibration in the motors. The proportional and derivative gains were adjusted individually. Once the correct value for the proportional gain was obtained, the derivative gain was adjusted. The integral gain was then increased until the KI value used produced zero position error. The table was determined to have zero position error if the user of the table was able to input coordinates to the opposite end of the table and the crossbar would transverse to this opposite end and stop with no space between the linear pillow block and the physical hard stop of the table. Tuning the x-axis motor resulted in gains of 20, 0, and 40 for the KP, KI, and KD, respectively. Similar tuning of the y-axis motor resulted in gains of 55, 0, and 40 for the KP, KI, and KD, respectively. The y-axis motors KP was set significantly higher because it would not hold position properly at lower KP values.

Because the system was designed with no limit switches, the physical dimensions of the workspace were defined using hard stops. Located at the beginning of every program was a homing subroutine. This subroutine's only purpose was to identify the physical dimensions of the X-Y table. The homing subroutine used the motors' torque limits to determine when a physical limitation in the table workspace had been reached. The subroutine first set the torque limits on each of the motors to low values that would be easily exceeded if the table's crossbar housing was driven into a built-in hard stop. The homing subroutine would first drive the x-axis until the crossbar housings reached the physical hard stop. There is one x-axis crossbar housing located on each of the x-axis rails, while an identical configuration is implemented on the y-axis rails. Figure 16 shows the crossbar housing attached to the linear rail and the physical hard stop being the corner support on the left. The hard stop would cause the torque limit on the motor to be exceeded. The subroutine would set the absolute position of the x-axis to 0. After this, the homing subroutine would drive the x-axis in the opposite direction until it hit the corner support on the opposite end of the table. The torque limit on the motor would again be exceeded, and the absolute position of the x-axis would be recorded as ΔX. An identical process would be followed to home the y-axis of the table. Following the completion of the homing subroutine, the table dimensions in terms of encoder counts would be known for the apparatus.

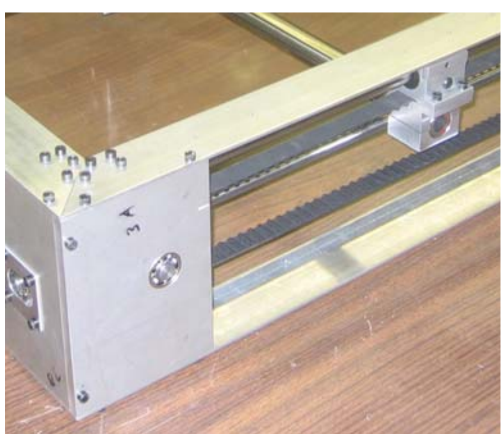


Figure 16 - Crossbar Housing & Physical Hard Stop

Tracing Program

The first program written for the X-Y table simply traced the outermost boundaries of the table's workspace. The primary purpose of this program was to gain familiarity and experience with the coding software. After homing the system, the physical dimensions of the workspace would be known. The program would then move to the (0, 0) coordinate to begin the motion profile. The table would move to the coordinates (ΔX, 0), then (ΔX, ΔY), followed by (0, ΔY), and lastly return back to its original starting position of (0, 0). The physical dimensions of the apparatus were defined and recorded in terms of encoder counts. The program then prompts the user to run the program again or to exit the program. The program is designed with a torque limit to ensure the safety of the test subject. If the torque limits are ever exceeded, the motion of the motors is halted, and the program is exited. This program was later modified to allow the user to define the size of the rectangle in terms of inches. The encoder was a 1000 count unit with quadrature. The circumferential travel along the pulleys was given by Equation 2, where 2.387" is the pitch diameter for the pulley. The linear translation of the table was calculated using Equation 3**,** the circumferential travel along the pulley based on its pitch diameter divided by the product of the lines per revolution and the quadrature.

Equation 2

$$\frac{2.387(in)*\pi}{1(rev)} = 7.5(in/rev)$$

Equation 3

$$\frac{7.5(inch/rev)}{1000(line/rev)*4(counts/line)} = 0.001875(inch/count)$$

Along with giving the user the option to decide the rectangular dimensions, the user was also now able to decide where the corner of the rectangle started. Once the starting position is specified, the user is prompted with the workspace still available to trace his/her rectangle profile. Following this prompt, the user is asked to specify the rectangle dimensions.

Rectangle/Circle Program

The second program designed was one that traced the profile of either a rectangle or a circle. The primary purpose of this program was to begin introducing some user prompts and user-defined options. As in all of programs, the homing subroutine was completed before actual execution. The user is asked if he/she would like to trace either a rectangular or a circular profile. In both cases, the dimensions of the profiles are predetermined, and the user is unable to alter them. After selection and execution of the desired profile, the user is asked if he/she wishes to run the program again.

Reaching Program

The final program written for the X-Y table was designed to put the subject through various reaching routines. The subject was able to define a reaching motion in any direction in front of him/her. The program allows the subject to decide if he/she wants to reach anywhere from his/her extreme left to his/her extreme right. The relative angular reaching motion is defined in degrees. The subject is allowed to choose any angular displacement between 0° and 90° of either side of his/her body. A 0° angular displacement would coincide with a reaching motion directly in front of the subject, while a 90° angular displacement would coincide with a reaching pattern either directly to the right or to the left of the subject. The subject was capable of deciding if he/she wanted to reach to the right or to the left by an input that was chosen after the angular displacement. The purpose of this program was to write a completely user-controlled program. The secondary purpose was to establish a program that more closely fit some of the tests that would be preferred in later experimentation. As in the previously discussed programs, this program included a torque limit to ensure the safety of the test subject. The torque limit was more crucial in this program because of the possibility of it actually being used with a test subject. A flowchart for the reaching routine is located in Figure 17.

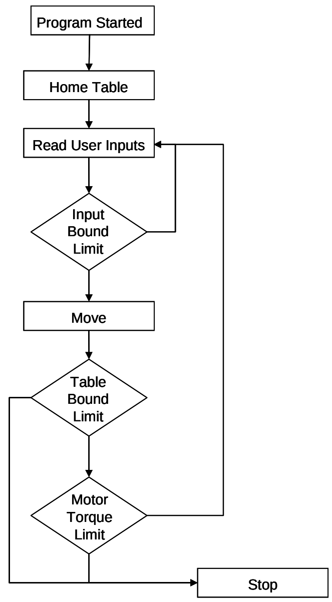


Figure 17 - Reaching Program Flowchart

Active Assist

In the future, it will be desired to conduct an active assist experiment. The experiment will consist of an individual initiating motion in a desired direction and receiving assistance from the X-Y table. The X-Y table will read the forces exerted, and if those forces exceed a threshold, the motors will assist the subject in that direction. A force threshold will be implemented to ensure that the subject is moving under his/her own effort and the device is merely assisting the movement in that direction. This threshold will be designed with a deadband. The deadband region will consist of an upper threshold that must be exceeded to start the active assistance and a lower threshold that must continue to be exceeded in order for active assistance to remain. This region is implemented due to the slight drop in the forces applied as motion is underway and motor assistance is initiated. The starting force required in the system will always be greater than the force required to keep the table moving at a constant velocity. The controller is able to monitor velocities, position, and forces during the experimental routine.

All of the actively assisted motions will be practiced over the subject's entire available range of motions. Each subject will have a unique user-defined workspace not to be exceeded during testing. The workspace will be pre-assigned in each direction prior to the start of experimentation. The subject will be asked to extend his/her arm and the handle out to the furthest extent in each direction without experiencing any pain. This value will be recorded and noted as a workspace limit. As the individual approaches one of these workspace limits, the motors will discontinue assistance, and the table will essentially be un-powered.

The premise for designing the active assist program is to act as a precursor to the eventual adaptive force routine. In the adaptive force field program, a subject will be given a target position in the workspace and instructed to reach for it. If the subject accurately moves towards the target, the X-Y table will actively aid in the motion. If the subject were to veer off course from the target, the X-Y table will apply a force field in the direction of the desired target to assist the subject in reaching the target. The difference between the active assist program and the adaptive force field program is in the addition of the repulsive forces if motion is conducted in the wrong direction. In the adaptive force field program, the device will only aid in motion in the proper direction and will repel incorrect motion.

CHAPTER 4 – SYSTEM COMPLICATIONS

Component Interference

Upon assembly of the X-Y table, an unwanted interference was observed between the pillow blocks and the machined base of the device. This unforeseen interference occurred due to the interface between the pillow blocks and the low profile rails. The base was originally designed to have 0.065” of clearance between the lip of the base and the pillow block. The pillow blocks are designed to rotate slightly off center of the low profile rails to allow for torsional misalignments. Figure 18 is an illustration of this misalignment. Because of this feature, after the crossbar shafts were installed, the pillow blocks tended to rotate in toward the lip of the base rail. Without the crossbar shafts, the bushing pillow blocks would slide along the low profile rails as intended, but with the crossbar shafts, there was a substantial amount of interference. Figure 19 is a picture of the actual interference. It was later observed that after the four drive shafts and the two crossbar shafts were installed, the stiffness of the table increased greatly. It became apparent that the lips on the base were unnecessary, so they were removed as shown Figure 20.

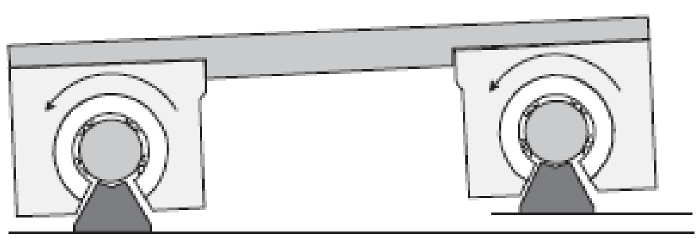


Figure 18 - Torsional Misalignment Illustration

Figure 19 - Area of Component Interference

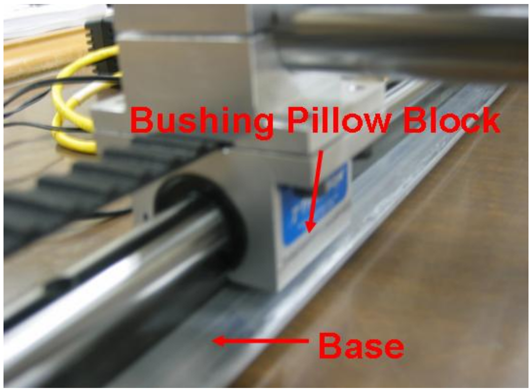


Figure 20 - Base with Lip Removed

Crossbar Shaft & Bearing Friction

After the component interference issue had been addressed, the system still continued to run along the shafts in a stiff manner. When the linear bearings ran along the crossbar shafts, there was unwanted friction. The linear bushing bearings were supposed to operate with a coefficient of friction as low as 0.001. The friction problem was not evident if the linear bearings were run along the crossbar shafts without being housed in the crossbar bearing housing located in Figure 21. The problem was that the crossbar bearing housing had been tightened down too tightly on the linear bearings. This led to the balls within the bearings being pressed into the crossbar shafts, not allowing the bearings to slide along the crossbar shaft as intended.

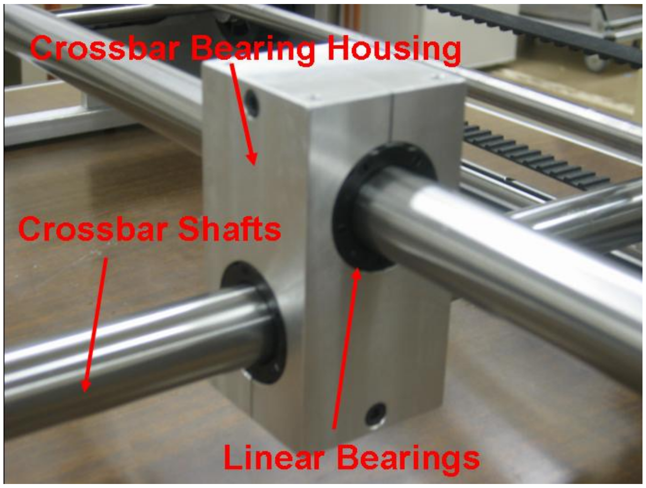


Figure 21 - Bearing Friction Location

Motor Overheating

An overheating problem in the motors was discovered. After approximately 15-20 minutes of continuous operation, the motors in the X-Y table began to run hot. Initial troubleshooting suggested that the motors' armatures had to be incorrectly wired to the amplifier. According to the motor manufacturer's wiring diagram, the red wire corresponds to armature A, the white wire to armature B, and the black wire to armature C. The A, B, and C motor armatures, however, didn't correspond to the A, B, and C connection ports of amplifier. With there being three armatures on each motor, there were six possible connection configurations with the amplifiers. To find the correct configuration, the motor had to be run through all six configurations. Characteristics recorded for each configuration were if the motor ran, ran smoothly throughout the velocity profile used to test each configuration, and ran without any unwanted noises.

The results of the overheating investigation yielded two wiring configurations that resulted in motor operation that ran smooth without unwanted noises. The first wiring configuration that ran smoothly without any noise was the configuration provided in the manufacturer's wiring diagram. The second wiring configuration was one that corresponded to the white wire as A, black wire as B, and red wire as C. The recommended wiring configuration produced the results that overheated after a few minutes of continuous operation, while the other configuration resulted in proper operation without any overheatin. A tabular representation of the results of the overheating investigation is located in Table 1. The second motor that wasn't subjected to the overheating investigation was later wired in the same configuration that yielded acceptable results for the first motor. This motor was then observed in continuous motion for several minutes to confirm that its definitions of A, B, and C corresponded with those of the first motor tested.

One thing that should be noted regarding the overheating investigation is that it had to be conducted very carefully. Because the motors were essentially going to be hooked up incorrectly five out of six times, permanent damage could result if they were run in this configuration for too long. The pre-programmed velocity profile was immediately aborted at the first sign of improper operation. Also because the first configuration tested was the one that caused substantial overheating, the motor was given adequate time to properly cool before the remaining wiring configurations were tested.

Table 1 - Overheating Motor Investigation Results

Armature			Comments
A	B	C	
Red	White	Black	Motor runs smooth at high speeds, runs hot
Red	Black	White	Motor runs, strange noise while at start up and high speeds
White	Red	Black	Motor runs, strange noise while at start up and high speeds
White	Black	Red	Motor runs smooth at high speeds
Black	Red	White	Motor does not run at all
Black	White	Red	Motor runs but not smoothly and makes strange noise

Motion Inconsistency

A major problem encountered while testing the X-Y table was motion inconsistency between the x-axis and y-axis. When the system was un-powered and driven manually from the handle, the y-axis performed considerably better than the x-axis. Uniformity was required to conduct accurate testing. If one axis performed better than the other, it would alter the overall effectiveness of the testing.

Initial thinking was that the motion inconsistency problem could be corrected with appropriate belt tensioning. With the y-axis already operating correctly, the tensioning device for the x-axis was tensioned to match the tension of the y-axis. The tension was measured based on feel. When the performance of the x-axis did not get better, additional levels of tensioning were investigated. After none of the tensions produced improved results, an attempt to degrade the y-axis performance by loosening the tension was made. When the poor performance of the x-axis could not be recreated in the y-axis, it became apparent that the problem was more involved than the tension.

The X-Y table was taken apart component by component to determine at what assembly level the problem started to occur. The crossbar bearing housing and bearings were the first components removed to make the x-axis and y-axis independent. The thinking was that there may be binding due to slight misalignments between the axes and decoupling their respective movements would eliminate any binding. This investigation led to no change in performance. The next step was to remove the crossbar shafting all together to decouple the movement of pillow blocks for each axis. Essentially all four sides of the table where now able to operate independently. Again this removal led to no improvement. The final component removed was the crossbar housing. The crossbar housing clamps to the pillow block, sandwiching the timing belt in between. Removing the crossbar housing decouples the timing belt from the linear rail system. The linear rails were ruled out as the source of the problem when performance in the x-axis still failed to improve. With the investigation complete, it was determined that the motion inconsistency was due to the timing belts for the x-axis not meshing properly with the pulleys.

The belts were sent back to the supplier, but the supplier was unable to locate or pinpoint any defects in the belts. A comparison of the good belts used on the y-axis and the defective belts used on the x-axis, it was noticed that the two belts had come from two different manufacturers. The y-axis belt was a Gates Corporation belt, while the x-axis belt was a Bando USA belt. The pulleys with which both belts meshed came from Gates. Because the problem was now known to be a mismatched belt and pulley combination, the solution was to properly pair the two with a combination that came from the same manufacturer. Since the appropriate length Bando belt had already been purchased, focus turned to finding a Bando pulley that shared the same tooth profile as the belt. When it was discovered that Bando did not also supply pulleys, the focus shifted to identifying a Gates belt in the same length and tooth profile as the Bando belt. Gates makes no belts that met the pitch length requirement, and alternative belt and pulley tooth profile options would have required major hardware modifications to the existing X-Y table. Any change to the pulley diameter would alter the assembly stack-up of all of the hardware, while a change in belt pitch length would require shortening the available workspace of the table. The existing design of the corner brackets did not allow enough material to lengthen the belt pitch length to the next standard size.

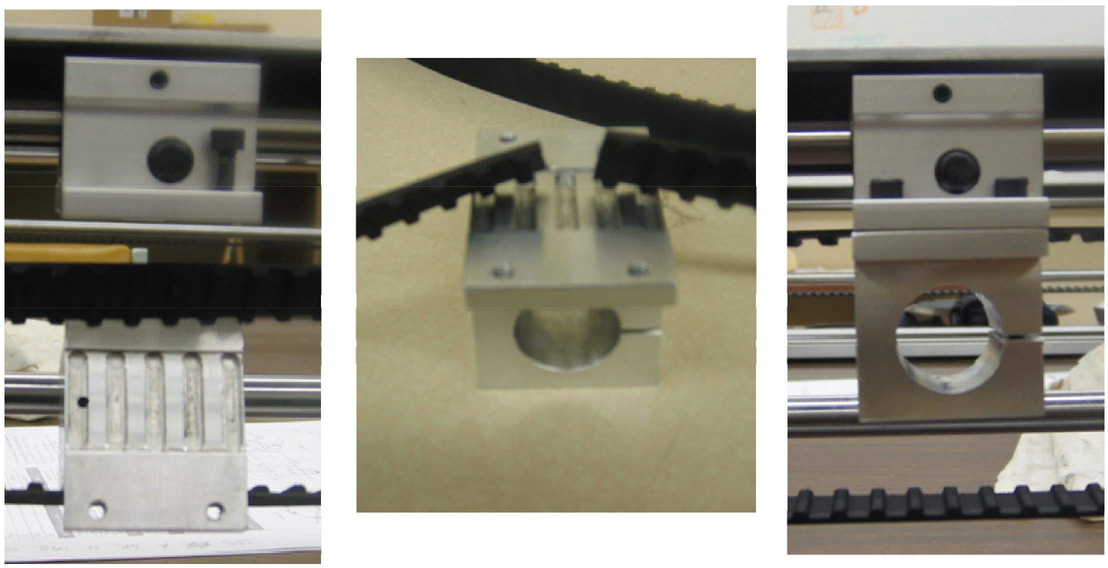


Figure 22 - Belt modification procedure

It was decided to use the existing pulleys and purchase new Gates belts that were of a pitch length that was one size too long. The belt was then cut to the appropriate pitch length and fastened to the X-Y table by sandwiching it between the machined pillow blocks and the crossbar housing. This modification produced the quickest and least labor intension solution. An illustration of this modification can be found in Figure 22. Because the crossbar housing had five grooves in it, there still was enough load carrying capability in the transmission system after the cut had been orchestrated. The fibers are the major load carrying components for the timing belts, so when the belts were cut, the rubber of the belts was forced to carry more of the load.

CHAPTER 5 – PROPOSED EXPERIMENTAL PROCEDURE

A wide range of experiments can be conducted with the X-Y table due to its flexibility. The goal was to create a system that was easy to operate for both the experimenter and the test subject. For the test subject, the test procedure needs to be as comfortable and unobtrusive as possible, while also remaining safe. Ergonomics need to be taken into account. The X-Y table is essentially a tabletop unit. If subjects feel that the tabletop mounting is not comfortable or adequate for future testing, the system will have to be repositioned, possibly recessing it within an existing table. For the experimenter, the device needs to be easy to operate while also having the ability to collect data. Visual Basic is employed to meet these requirements. An application specific Visual Basic program will be capable of both operating the system and recording the necessary data. Visual Basic is able to read and communicate with both the motion control card and the force sensing control card. This will allow both control cards to work together to produce all of the functions needed.

The following chapter outlines the proposed experimental procedure for testing. The experimental procedure is generic to whichever motion test is being conducted. It will be refined later for more specific testing applications. Within this chapter, there is a section discussing the replication of an existing experiment conducted on a different device. In this section, the test procedure for that test will be discussed along with any issues that arose while conducting the experiment on that device.

Proposed Experimental Procedure

All experiments will begin with the experimenter powering up the system. This consists of plugging in the power supply and powering on the computer. The experimenter will load the Visual Basic program that calls all of the motion profile programs. The interface will instruct the experimenter to choose the desired motion program for that testing session. The experimenter will home the system before proceeding any further. Once the homing sequence has run, the system will store its physical boundaries and have its origin defined. The system is now primed for testing.

The test subject must also be prepped prior to testing. The test subject will be outfitted with magnetic sensors to record arm position data. The sensors will be affixed to the skin of each subject. Preliminary sensor placement will be at the individual's wrist, elbow, and shoulder. The test subject will be positioned such that his/her fixed trunk anterior/posterior (A/P) axis will be aligned directly in the middle of the X-Y table. This positioning will allow for the greatest amount of useable workspace during testing. The test subject will not be restrained in any way. The test subject will be instructed to attempt to keep his/her chest and head fixed in a position directly in front of the X-Y table during testing. After carefully adjusting the height of the chair so that the test subject sits in a comfortable position, the subject is ready for physical reaching limitations to be measured. The subject will sit as if he/she is going to initiate a test routine and comfortably reach out to his/her left and rightmost extremes. At each extreme, the program will record the position as the individual's reaching limit. The same process will be conducted to record the individual's maximum reach straight out from his/her A/P axis. Upon completing these final procedures, the testing is ready to commence.

When the subject indicates that he/she is ready for testing to begin, the experimenter will begin the first trial. The experimenter will always remain at the computer to have complete control of the device. The test subject should remain comfortably seated in his/her chair until testing has concluded. In the event that something goes wrong during testing, an emergency stop button will be employed in the interface allowing the experimenter to quickly terminate the motion sequence.

The Visual Basic interface will allow for the easy download of the test data to an Excel spreadsheet for later processing. Applicable data will depend on the nature of the. Data may be pulled and recorded from the force transducer, magnetic sensors, motion control card, or any combination of the above.

Hand Motion Replication

Stephens [13] used a linear slide device to study human hand motion perception. Since Stephens desired the ability to move a subject's hand in a linear path and to change the orientation of that path, the natural choice for the device was a revolute-prismatic (RP) system.

In Stephens's tests, subjects were fit with goggles that had a perspective line projected into them. The linear slide of the device moved to the starting position and then began moving the subject's hand. Clicking of the left or right mouse button allowed the test subject to change the orientation of the linear slide. The subject attempted to align his/her hand motion with the line projected in the goggles. Once the subject believed that his/her hand was aligned, he/she clicked the center mouse button, and the final position was recorded. The test was repeated for a number of target orientations.

The versatility of the X-Y table allows for recreation of Stephens's tests. A worthwhile application of the X-Y table is to recreate the existing test and confirm the results. Although the X-Y table is a PP mechanism, the test setup can still be recreated. No hardware changes will be required to replicate the test. Since the X-Y table operates in Cartesian coordinates rather than the radial coordinates of Stephens's device, all of the modifications lie in the control scheme.

There are some issues that may arise during the experiment recreation. The handle of the X-Y table sits higher than the handle in the previous experiment. Adjusting the test subjects to the right height for adequate testing may require the use of a different mounting table. A worst-case scenario would call for modification of a table in which to recess the X-Y table. This would allow the handle to sit nearly flush with the tabletop. Another challenge is subject placement. In Stephens's tests, the subject was placed in varying orientations. In the case of the X-Y table, the test subject can align his/her A/P axis with the leftmost corner of the table allowing for motion that extends directly perpendicular to the tabletop edge and fans out in a clockwise direction. The subject can also align his/her A/P axis with the rightmost corner of the table which allows for motion that fans out in a counterclockwise direction. Another orientation is where the test subject will align his/her A/P axis with a corner of the table. This orientation will permit the individual to only reach 45° from their fixed trunk A/P. The final positioning possibility is to align the test subject's A/P axis halfway between each table side. This positioning would allow for full clockwise and counterclockwise rotation. It seems that the latter positioning would be the best for the test reproduction, but it would interesting to see if the test subjects react any differently when oriented at either the rightmost or leftmost corner of the table, knowing that there are physical limitations preventing them from rotating in one direction or the other.

CHAPTER 6 – CONCLUSIONS / RECOMMENDATIONS

This project involved the design of a device to be used in human force adaptation studies and possibly preliminary physical therapy. The machine was designed to apply forces to subject's upper limbs to conduct more extensive studies of motor coordination. The device was designed to safely interface with the subject's upper limb in either a powered or un-powered state. There are previously designed 5-bar mechanisms designed to do similar testing. These 5-bar mechanisms suffer from the limitation of variable apparent endpoint inertia that constrains the functional workspace available for testing. To achieve an isotropic apparent endpoint inertia throughout a large workspace, a 2-DOF X-Y table device was designed, built, and programmed with basic movement profiles. Preliminary results are promising, but more design and experimentation will be required before human subjects are tested.

Future Work

Because the preliminary programming only focused on achieving accurate motion profiles, work remains on integrating force sensing into the existing programs. Integrating force sensing involves Visual Basic to enable the terminal software for the motion control card to communicate with the terminal software for the load cell's control card. Visual Basic also allows for an easy-to-operate graphical user interface (GUI). The GUI will provide a means for safe operation of the system by any operator regardless of the individual's familiarity with the terminal software used to run the control cards.

Adequate sensors to measure joint angles will need to be identified and purchased. Sensors will be employed to measure joint angles. Being negligibly intrusive to the test subject during testing is a low-level requirement for the sensor selection. The sensor will also need to adequately resist any magnetic interference caused by existing components. Determining how many sensors will be required will be equally important. Ideally one would want to use the fewest sensors to adequately and accurately represent the joint angles of the test subject. The sensors will be attached to each individual's skin prior to testing, and the arm positioning results will be output to the computer.

After assembly of the X-Y table was complete, some operational observations were made. The handle was designed to screw into a mounting bracket that directly connected to the top of the load cell. The handle was designed with a height of 5". Although the handle was comfortable when used in un-powered testing, it caused excessive moments in the directions of motion. This was caused because the tolerance between the linear bushings and each axis shafting was not designed as close as expected. The tolerance allowed the crossbar bearing housing to rotate slightly about each axis shaft if a large force was applied perpendicular to the axis. In order to correct this problem, a handle redesign will likely be needed. The length of the handle will be shortened to decrease the moment rotation about the axis. A proposed change to the handle would be to make it a ball. The user would then operate the X-Y table in the same manner that they use a computer mouse. Additional thought will need to be devoted to this design to ensure that the change in hand orientation doesn't affect the results.

Summary of Work Completed

The design, assembly, and preliminary testing of the X-Y table have been completed. A significant amount of work is still needed for the project. Implementation of force sensing in the existing motion programs must be completed before testing can take place. The work completed on the X-Y table has led to a system that has fairly constant apparent endpoint inertia, capable of providing forces of 44.5 lbf. The early performance results of the table are promising, and the future looks bright for the project.

APPENDIX

Part Description	Manufacturer	Part Number	Contact Information	Quantity	Price	Net
Mini 45 Force Transducer	ATI Industrial Automation	9105-MINI45-R-1.8-M2-M1PCI	www.ati-ia.com	1	$6,000.00	$6,000.00
Second DAQ Transducer Calibration	ATI Industrial Automation	9105-DAQ-DUALCAL-A	www.ati-ia.com	1	$425.00	$425.00
Controller	Galil Motion Control		www.galilmc.com	1		$0.00
Interconnect Module	Galil Motion Control		www.galilmc.com	1		$0.00
Amplifier	Advanced Motion Controls		www.a-m-c.com	2		$0.00
Power Supply	Advanced Motion Controls		www.a-m-c.com	1		$0.00
Motors	Emoteq		www.emoteq.com	2		$0.00
						$0.00
Heavy Duty Bellows Couplings (0.5 x 0.5, 2 inch long)	McMaster-Carr	6446K91	www.mcmaster.com	2	$83.50	$167.00
Super Smart Ball Bushing Pillow Block - Open Type	Danahar	SSUPBO-10	www.danahermotion.com	4		$0.00
Super Smart Ball Bushing Linear Bearing - Closed Type	Danahar	SSU-16	www.danahermotion.com	2		$0.00
Shaft Rail - Low Profile (30 inch long)	Danahar	LSRA10	www.danahermotion.com	2		$0.00
Shaft Rail - Low Profile (34 inch long)	Danahar	LSRA10	www.danahermotion.com	2		$0.00
LinearRace 60 Case Tubular Shafting (37.125 inch long)	Danahar	LRL-16-TU	www.danahermotion.com	1		$0.00
LinearRace 60 Case Tubular Shafting (41.50 inch long)	Danahar	LRL-16-TU	www.danahermotion.com	1		$0.00
Timing Belt Pulley	Stock Drive Products	A 6Z 4-20DF07516	www.sdp-si.com	8	$15.58	$124.64
Timing Belt (78 inch long)	Stock Drive Products	A 6R 4-208 075	www.sdp-si.com	2	$37.01	$74.02
Timing Belt (72 inch long)	Stock Drive Products	A 6R 4-192 075	www.sdp-si.com	2	$30.40	$60.80
High Torque Series Motor	Emoteq	HT03004	www.emoteq.com	2		$0.00
5000 Ball Bearings	Stock Drive Products	A 7Y55-P 11250	www.sdp-si.com	8	$16.32	$130.56
Retaining Rings	Stock Drive Products	S73HW2-100-050	www.sdp-si.com	8	$2.28	$18.24
Motor Drive Shaft Short - (OD 0.5", Length 48", See Drawings)	McMaster-Carr	6061K73	www.mcmaster.com	1	$28.85	$28.85
Motor Drive Shaft Long - (OD 0.5", Length 48", See Drawings)	McMaster-Carr	6061K73	www.mcmaster.com	1	$28.85	$28.85
Pulley Drive Shaft Long - (OD 0.5", Length 48", See Drawings)	McMaster-Carr	6061K73	www.mcmaster.com	1	$28.85	$28.85
Pulley Drive Shaft Short - (OD 0.5", Length 42", See Drawings)	McMaster-Carr	6061K636	www.mcmaster.com	1	$26.77	$26.77

Machine Operation Instructions

1. Properly lubricate all of the linear rails
    a. In order to lubricate the Thomson low profile rails, remove the plug on each pillow block and using an oil gun squeeze 1-2 times. Reinsert plug.
    b. In order to lubricate the Thomson shaftings simply apply a moderate amount of oil to a rag and wipe along rails.
    c. Following the lubrication of all the rails manually drive the table several times to ensure uniform lubrication throughout.
2. Login to computer and open DMC Smart Terminal.
3. Ensure that control card is connected to interconnect module.
4. In upper left Command Window type MO followed by hitting the enter key in order to ensure motors are turned off.
5. Plug in power supply.
6. In lower right Program Editor Window go to file and open the desired program to be run.
7. Note the program name located at the top of the Program Editor Window. The program name will be in the following format, "#PROGRAM".
8. In lower right Program Editor Window go to file and choose Download to Controller option.
9. In upper left Command Window type SH followed by hitting the enter key in order to turn the motors on.
10. In the Command Window the command XQ #PROGRAM in order to begin executing the program.
11. Follow the program prompts outputted in the lower left Response Window.
12. After experiments have been completed the following procedures should be followed.
    a. In the Command Window turn the motors off with the MO command.
    b. Unplug the power supply.
    c. Close the DMC Smart Terminal program.

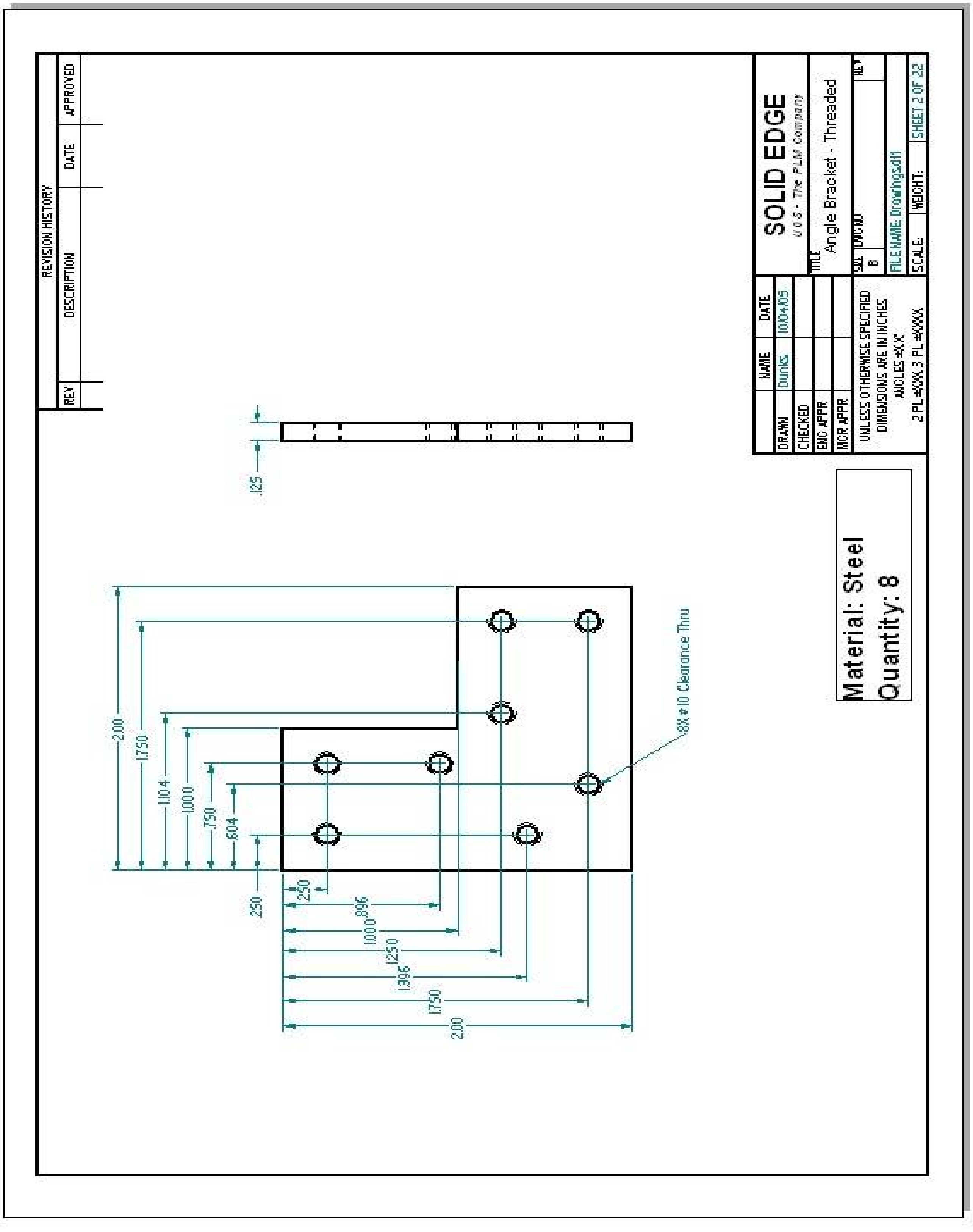
Notes:

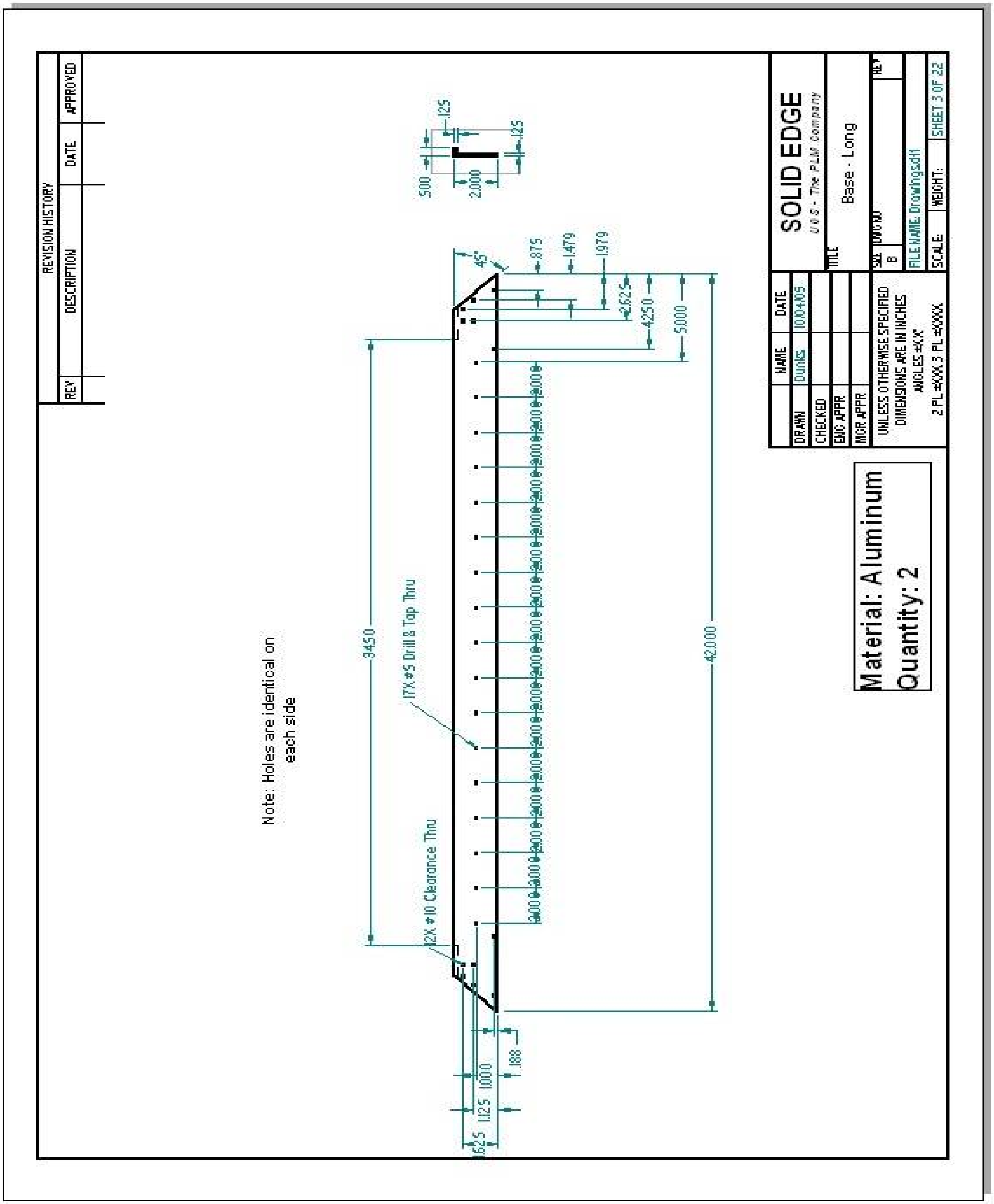
1. If no motion is observed after program has been executed, then motors may be off. Use the SH command to turn the motors on.
2. If program must be aborted suddenly, use the command AB in the Command Window.
3. Abort command will not work if program is prompting a user for a response in the Response Window.
4. In case program gets stuck in a continuous loop the user can manually exit the loop by downloading the program again using the Download to Controller command. DMC Smart Terminal will prompt you that a program is already running and will ask you would you still like to download. Click yes.

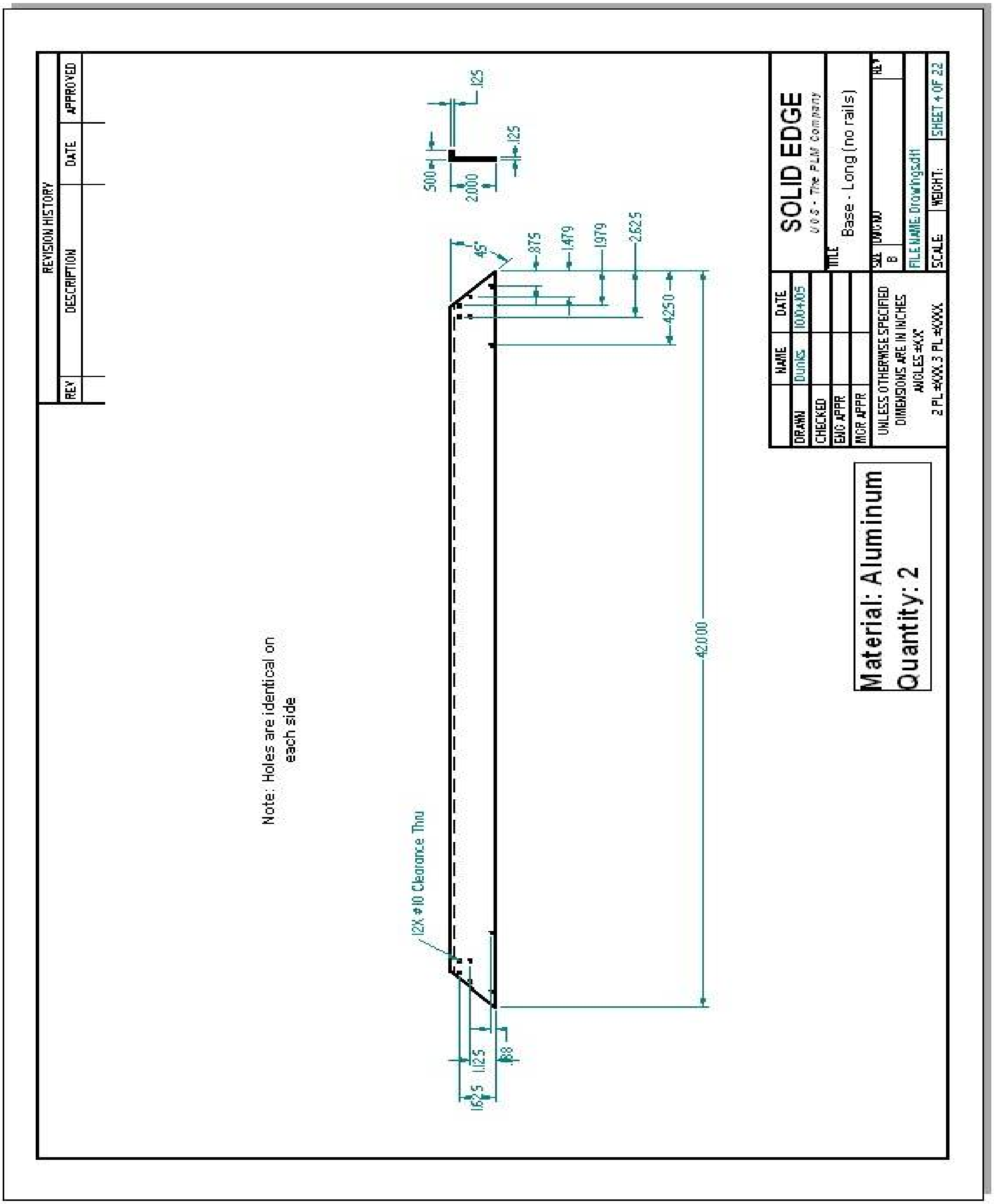
Machine Assembly Instructions

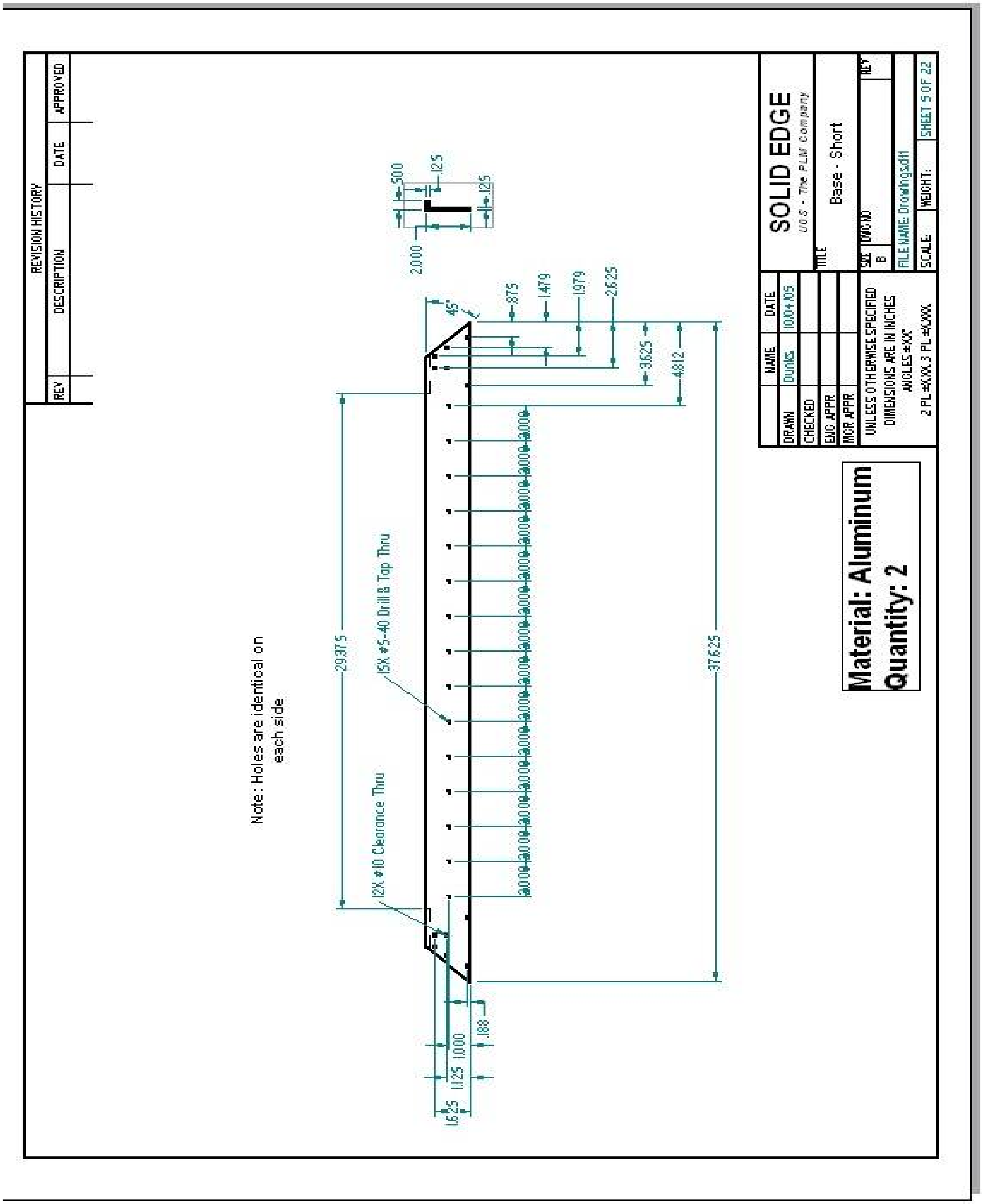
1. Assemble upper assembly
    a. Identify the two long base pieces with #5 holes
    b. Identify the two short base pieces without #5 holes
    c. Mate the corners of each short and long base with angle brackets
    d. Bolt long Thomson linear rails to both long sides of upper assembly
    e. Slide linear pillow block on each rail
2. Assemble lower assembly
    a. Identify the two short base pieces with #5 holes
    b. Identify the two long base pieces without #5 holes
    c. Mate corners of each short and long base with angle brackets
    d. Bolt short Thomson linear rail to both short sides of lower assembly
    e. Slide linear pillow block on each rail
3. Assemble each corner support
    a. Corresponding numbered supports go together
    b. Drive shaft holes should be offset height
    c. Press fit ball bearings in place
    d. Attach bearing plates where necessary
4. Connect lower assembly, upper assembly, and corner supports to create frame
    a. Corner supports belong in corresponding corner with number/letter tag
5. Run Drive shaft (short & long) through appropriate corner supports
    a. Slide appropriate pulley and timing belt in place
    b. Leave pulleys loose
6. Assemble crossbar housing assembly
    a. Place bushing bearing in crossbar housing
        1. Do not over tighten bearing in crossbar housing
    b. Run crossbars through crossbar housing
    c. Slide four pillow block attachments on each end of the two crossbars
7. Attach crossbar housing assembly to appropriate pillow blocks
    a. Make sure timing belts are positioned correctly on each side
8. Miscellaneous
    a. Tighten all bolts
    b. Place tensioning bolt in appropriate corner supports
    c. Equally tension each timing belt with its opposite timing belt

Engineering Drawings

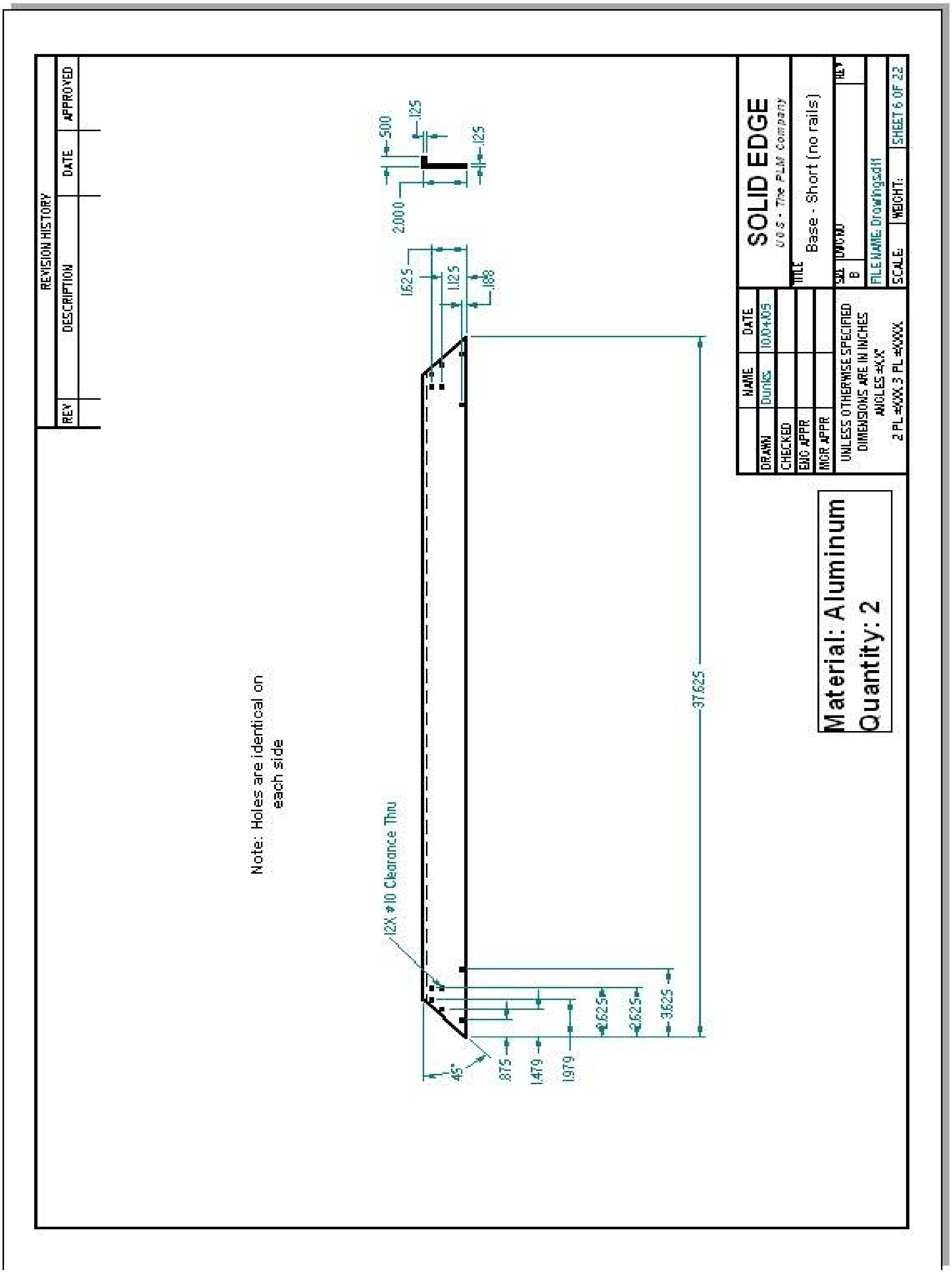


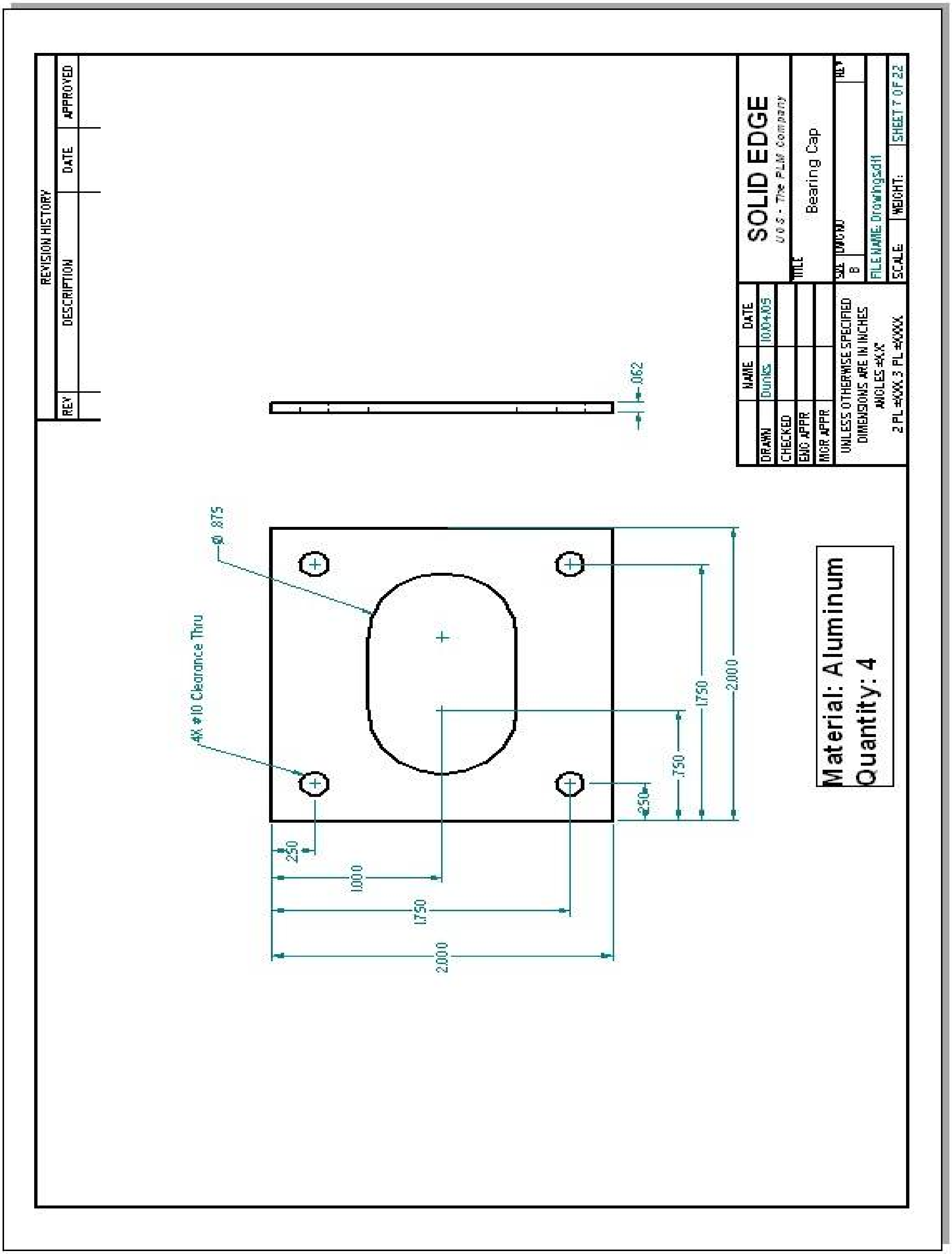

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Note: Holes are identical on each side
17X #5 Drill & Tap Thru
2X #10 Clearance Thru
34.50
42.00
Material: Aluminum
Quantity: 2
SOLID EDGE
UGS - The PLM Company
Base - Long
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
TITLE
SIZE
DWG NO
REV
B
FILE NAME: Drawings.dft
SCALE:
WEIGHT:
SHEET 3 OF 22

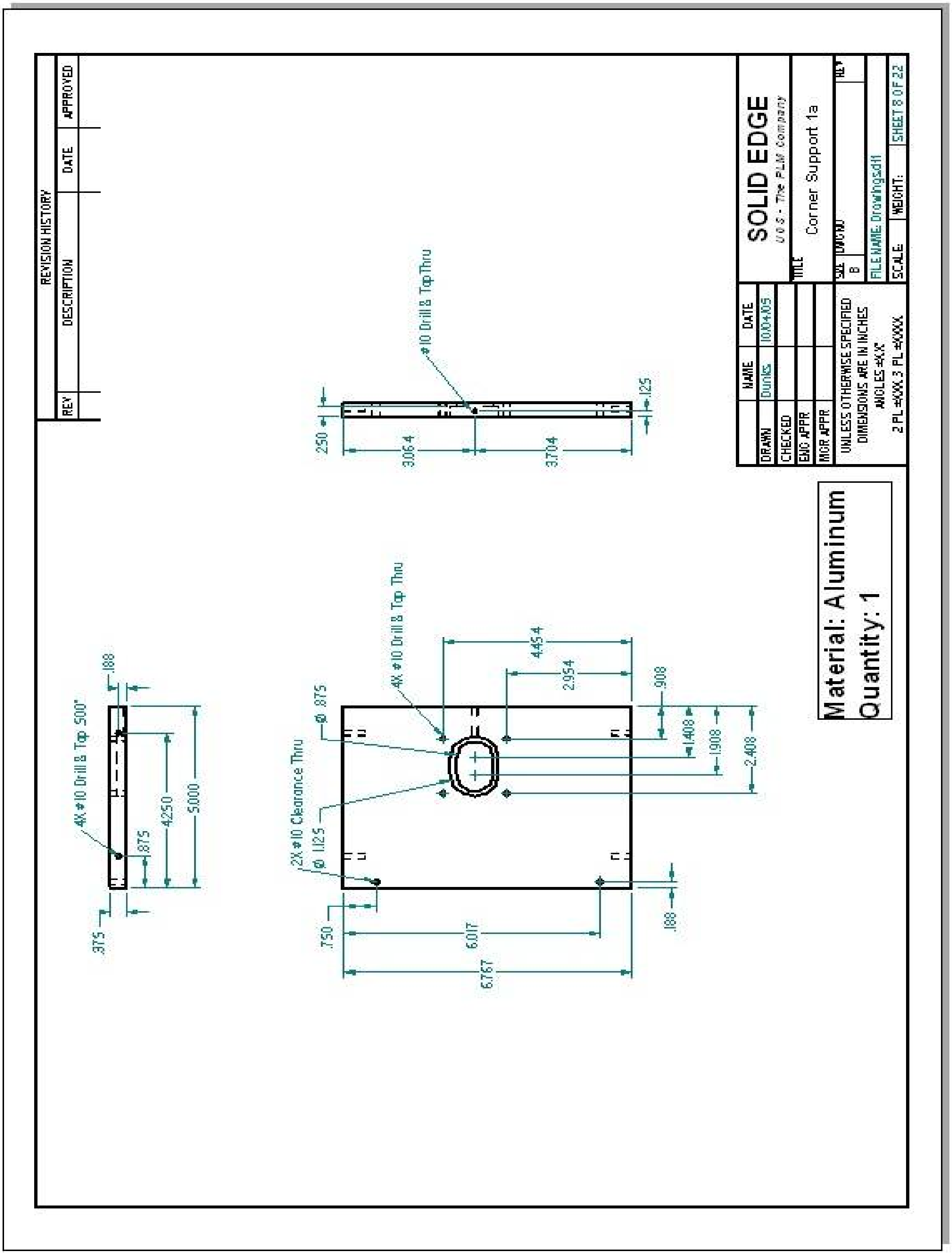

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Note: Holes are identical on each side
12X #10 Clearance Thru
45°
.875
1.479
1.979
2.625
4.250
42.00
.500
2.000
.125
1.625
1.125
.88
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
Base - Long (no rails)
SIZE
B
DWG NO
REV
FILE NAME: Drawings.dft
SCALE:
WEIGHT:
SHEET 4 OF 22
Material: Aluminum
Quantity: 2



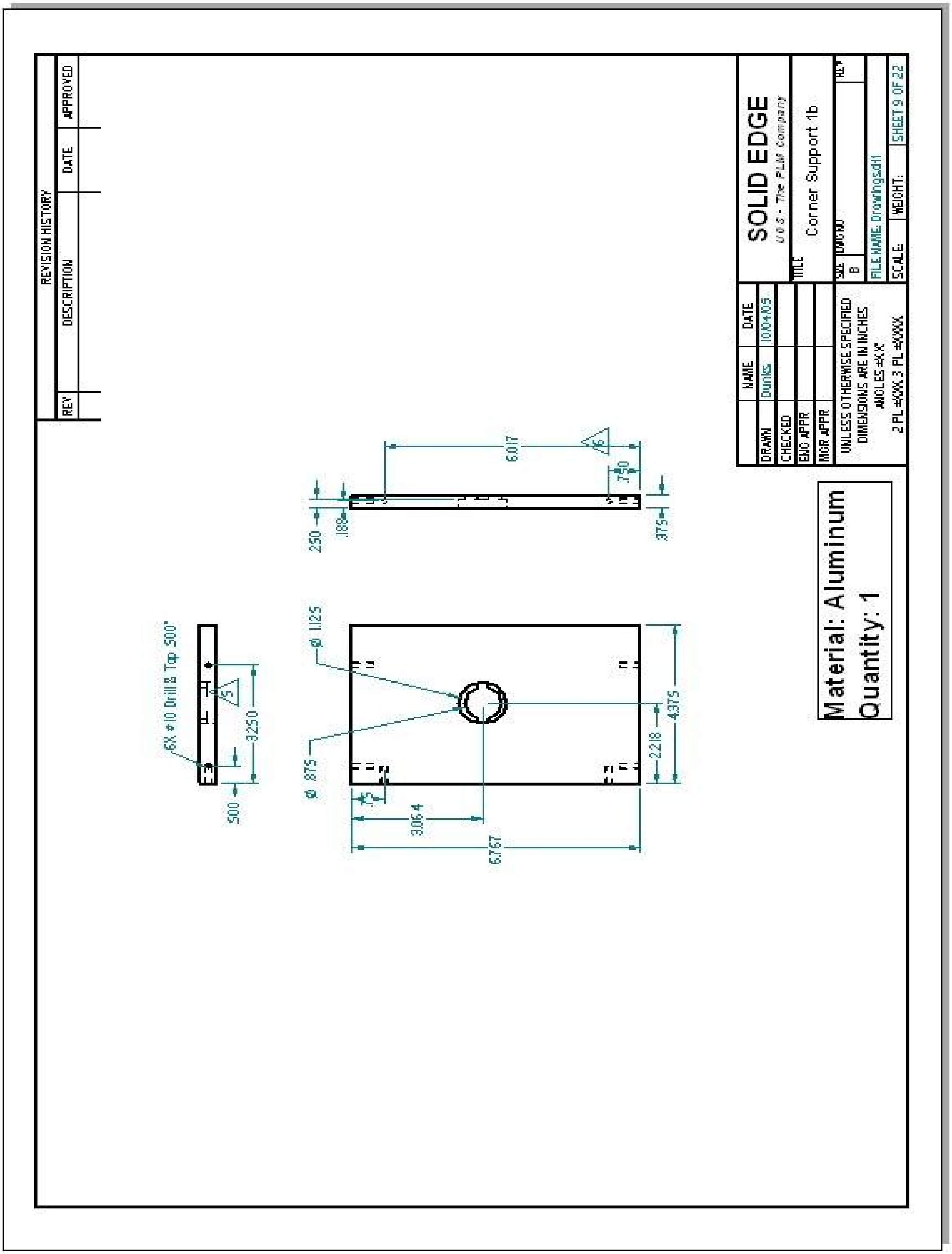
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Note: Holes are identical on each side
12X #10 Clearance Thru
15X #5-40 Drill & Tap Thru
29.375
37.625
Material: Aluminum
Quantity: 2
SOLID EDGE
Base - Short
DRAWN
Dunks
CHECKED
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
SHEET 5 OF 22

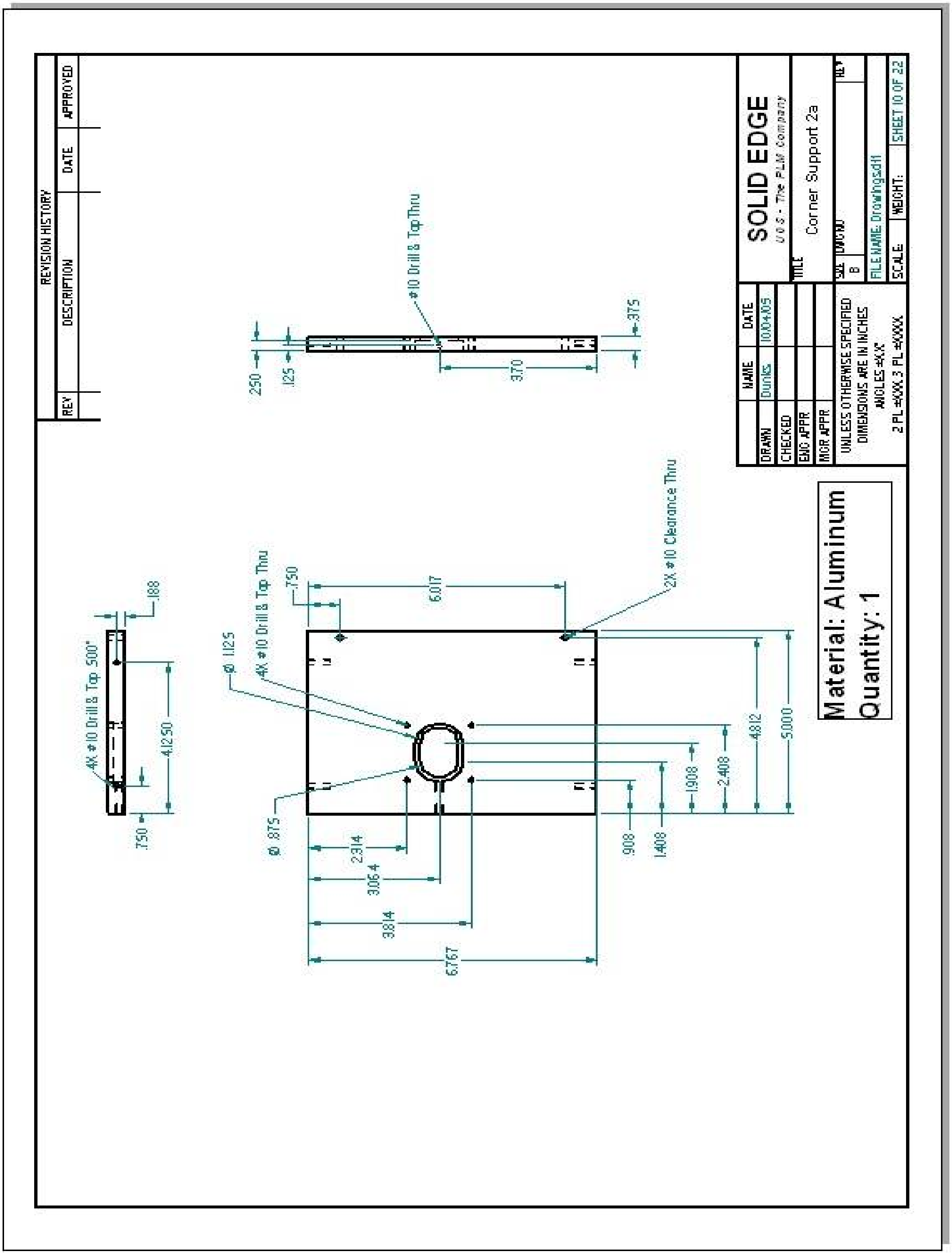

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Note: Holes are identical on each side
12X #10 Clearance Thru
45°
.875
1.479
1.979
1.625
2.625
3.625
37.625
1.625
1.125
.188
2.000
.500
.125
.125
Material: Aluminum
Quantity: 2
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
Base - Short (no rails)
SIZE
B
DWG NO
REV
FILE NAME: Drawings.dft
SCALE:
WEIGHT:
SHEET 6 OF 22


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
SOLID EDGE
UGS - The PLM Company
TITLE
Bearing Cap
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SIZE
B
DWG NO
REV
FILE NAME: Drawing.sdft
SCALE:
WEIGHT:
SHEET 7 OF 22
.062
Ø .875
4X #10 Clearance Thru
.250
1.000
1.750
2.000
.750
Material: Aluminum
Quantity: 4

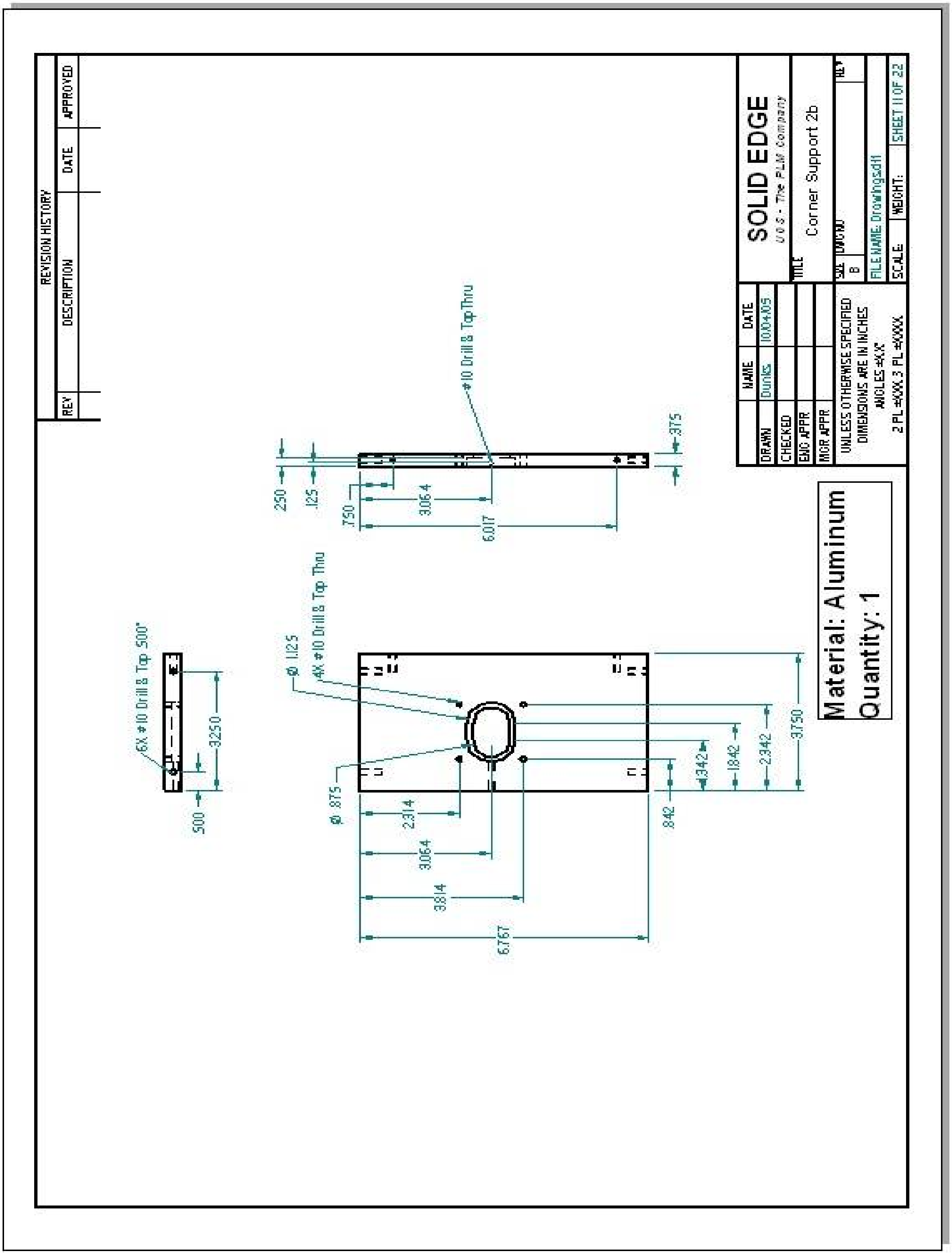


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
4X #10 Drill & Tap .500"
.188
.875
4.250
5.000
.375
2X #10 Clearance Thru
Ø 1.125
Ø .875
4X #10 Drill & Tap Thru
4.454
2.954
.908
1.408
1.908
2.408
.750
6.017
6.767
.188
#10 Drill & Tap Thru
.250
3.064
3.704
.125
Material: Aluminum
Quantity: 1
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
SOLID EDGE
UGS - The PLM Company
TITLE
Corner Support 1a
SIZE
B
DWG NO
REV
SCALE:
WEIGHT:
SHEET 8 OF 22

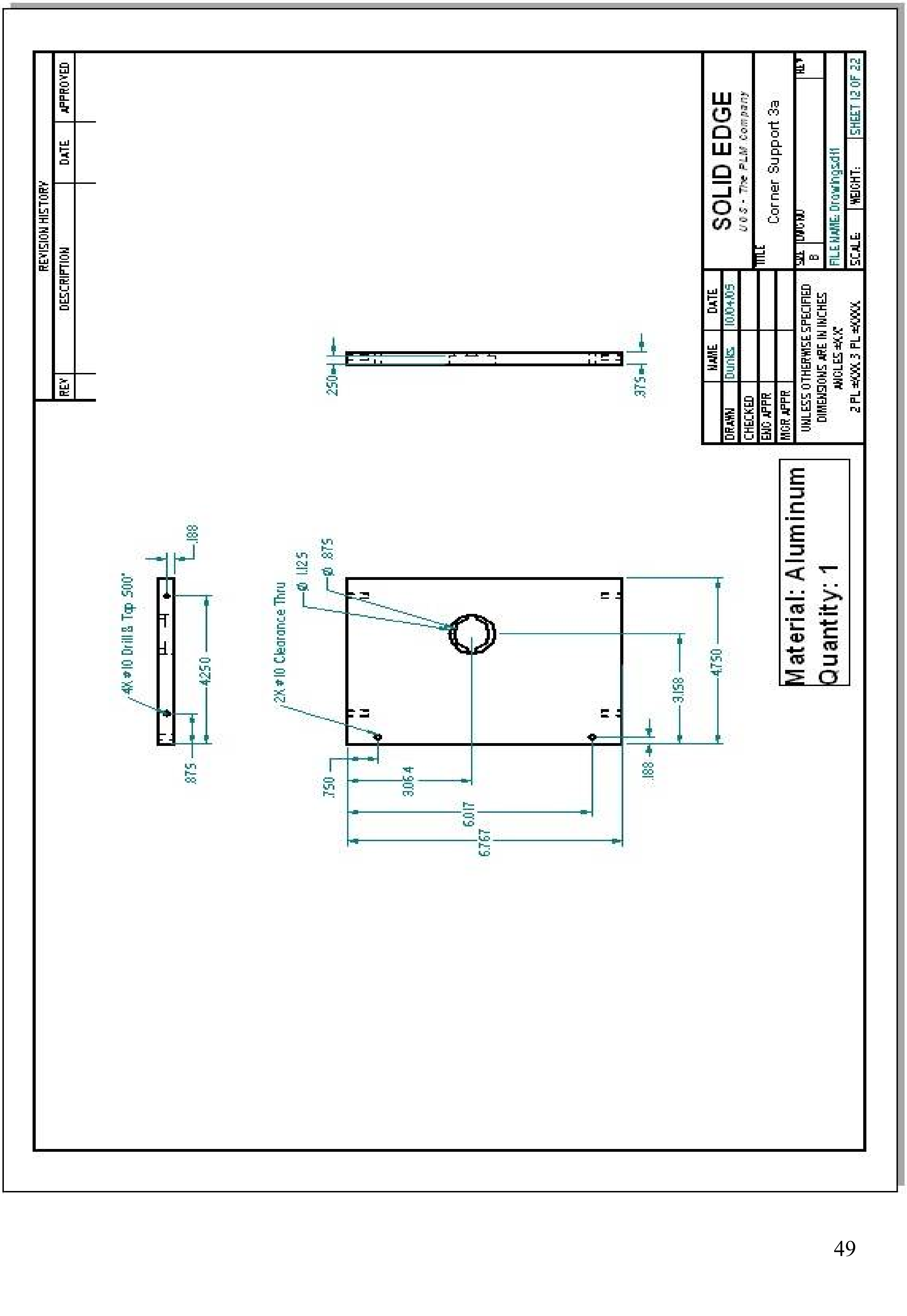

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
SOLID EDGE
UGS - The PLM Company
TITLE
Corner Support 1b
NAME
DATE
DRAWN
Dunks
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SIZE
B
DWG NO
REV
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 9 OF 22
Material: Aluminum
Quantity: 1
6X #10 Drill & Tap .500"
3.250
.500
Ø 1.125
Ø .875
2.218
4.375
3.064
6.767
6.017
.750
.250
.188
.375

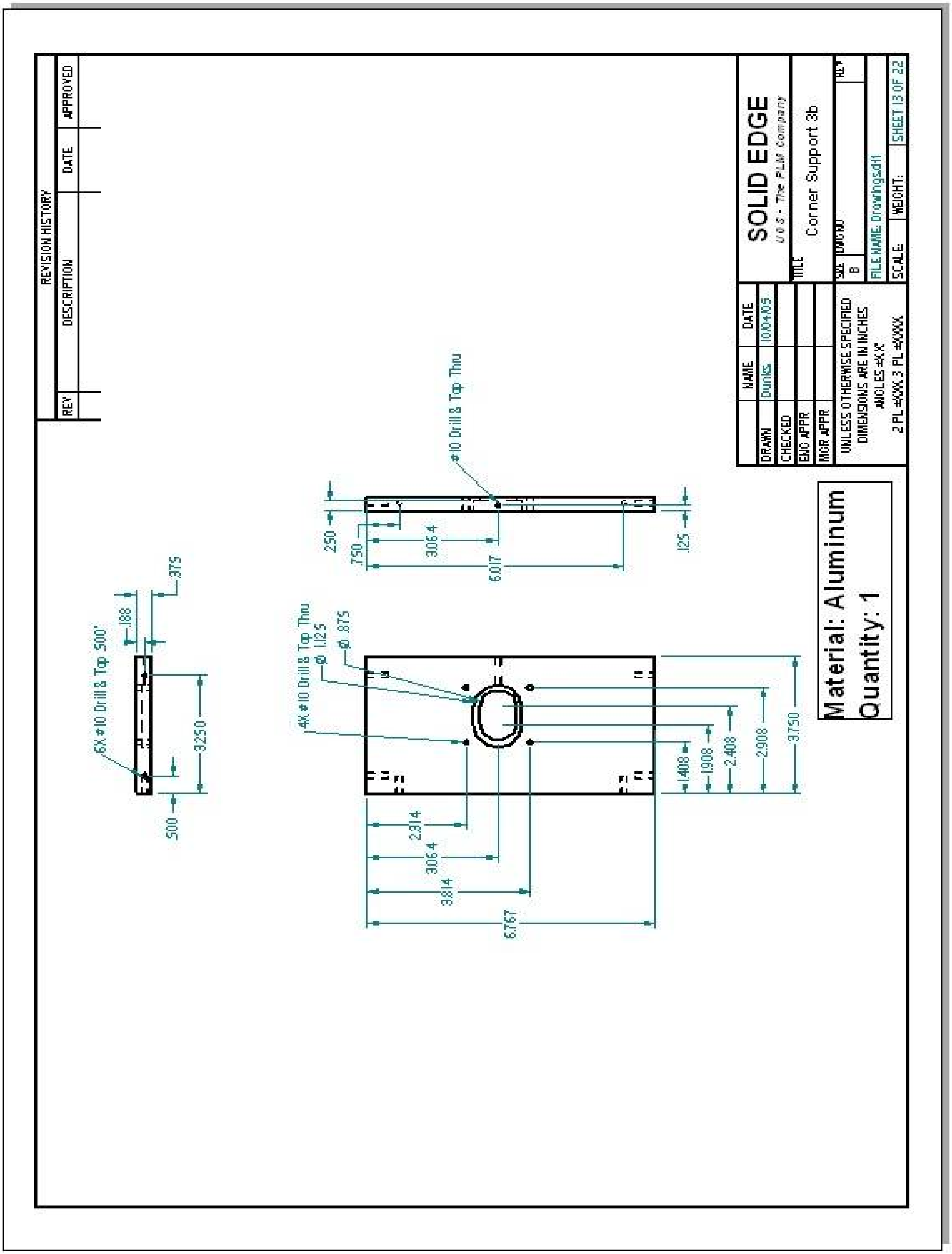


Material: Aluminum
Quantity: 1
SOLID EDGE
UGS - The PLM Company
Corner Support 2a
REVISION HISTORY
DRAWN Dunks 10/04/05
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
FILE NAME: Drawingsdft
SHEET 10 OF 22

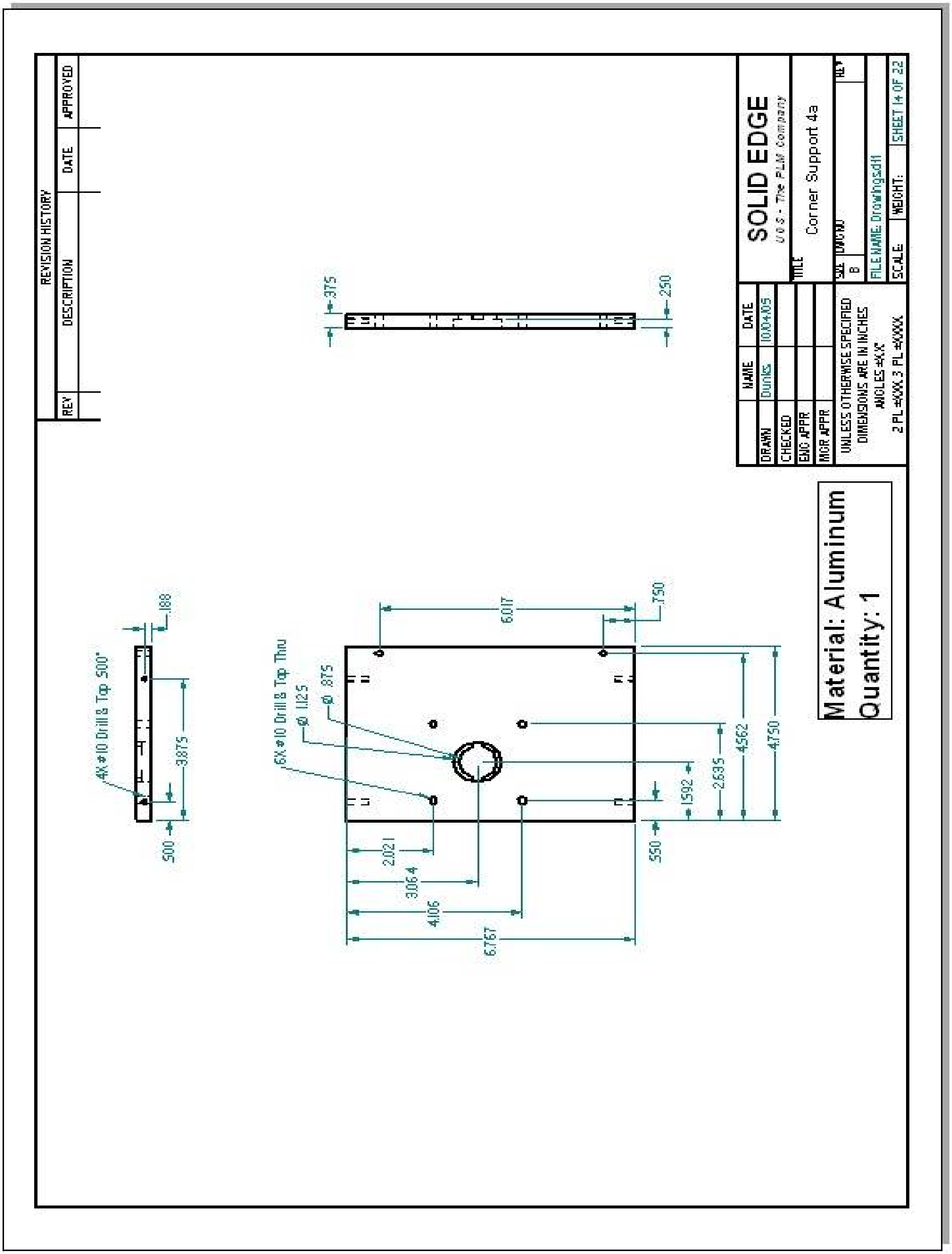


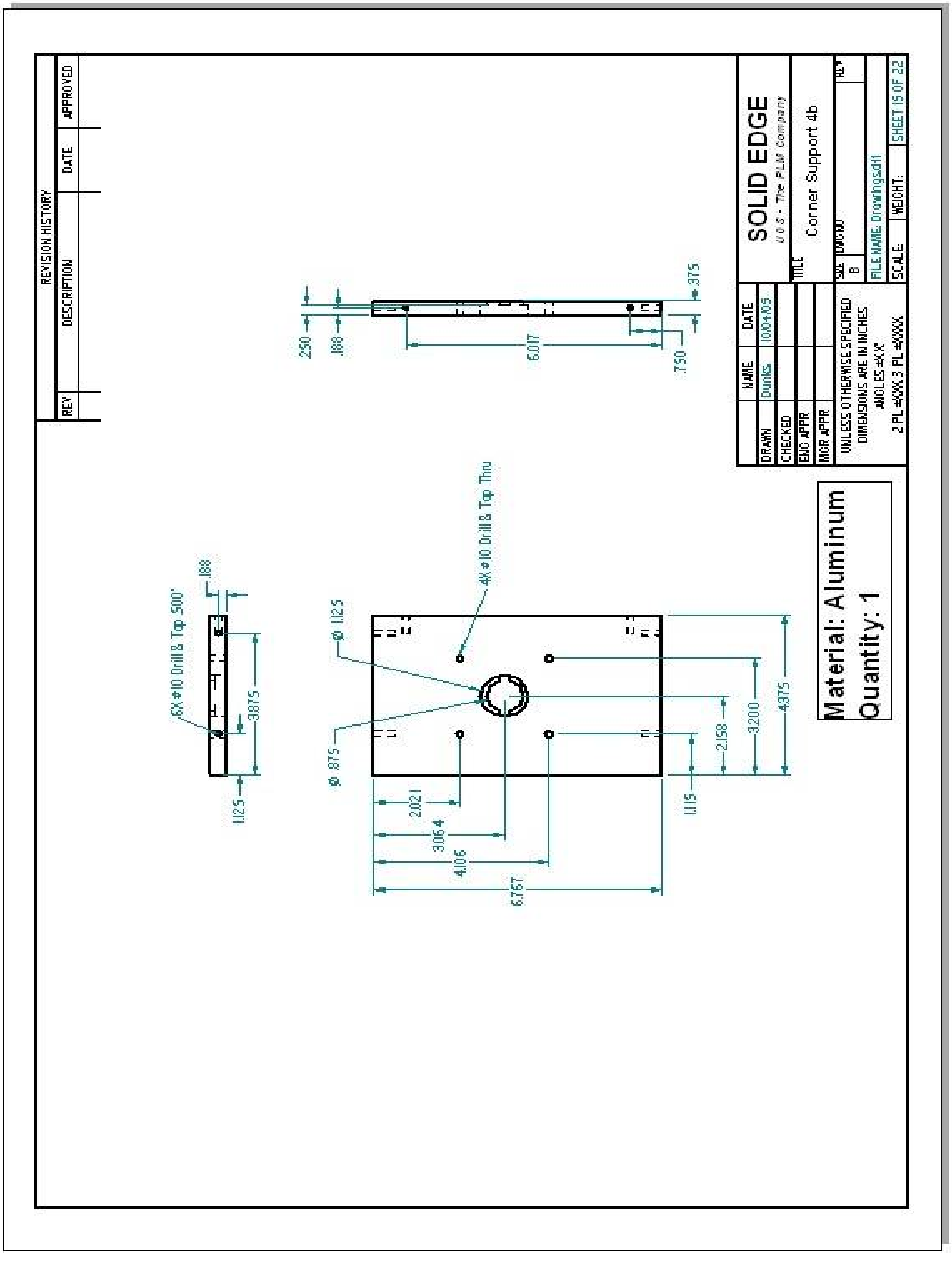
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
6X #10 Drill & Tap .500"
.500
3.250
Ø 1.125
4X #10 Drill & Tap Thru
Ø .875
2.314
3.064
3.814
6.767
.842
1.342
1.842
2.342
3.750
#10 Drill & Tap Thru
.250
.125
.750
3.064
6.017
.375
Material: Aluminum
Quantity: 1
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
Dunks
DATE
10/04/05
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
Corner Support 2b
SIZE
B
DWG NO
REV
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 11 OF 22

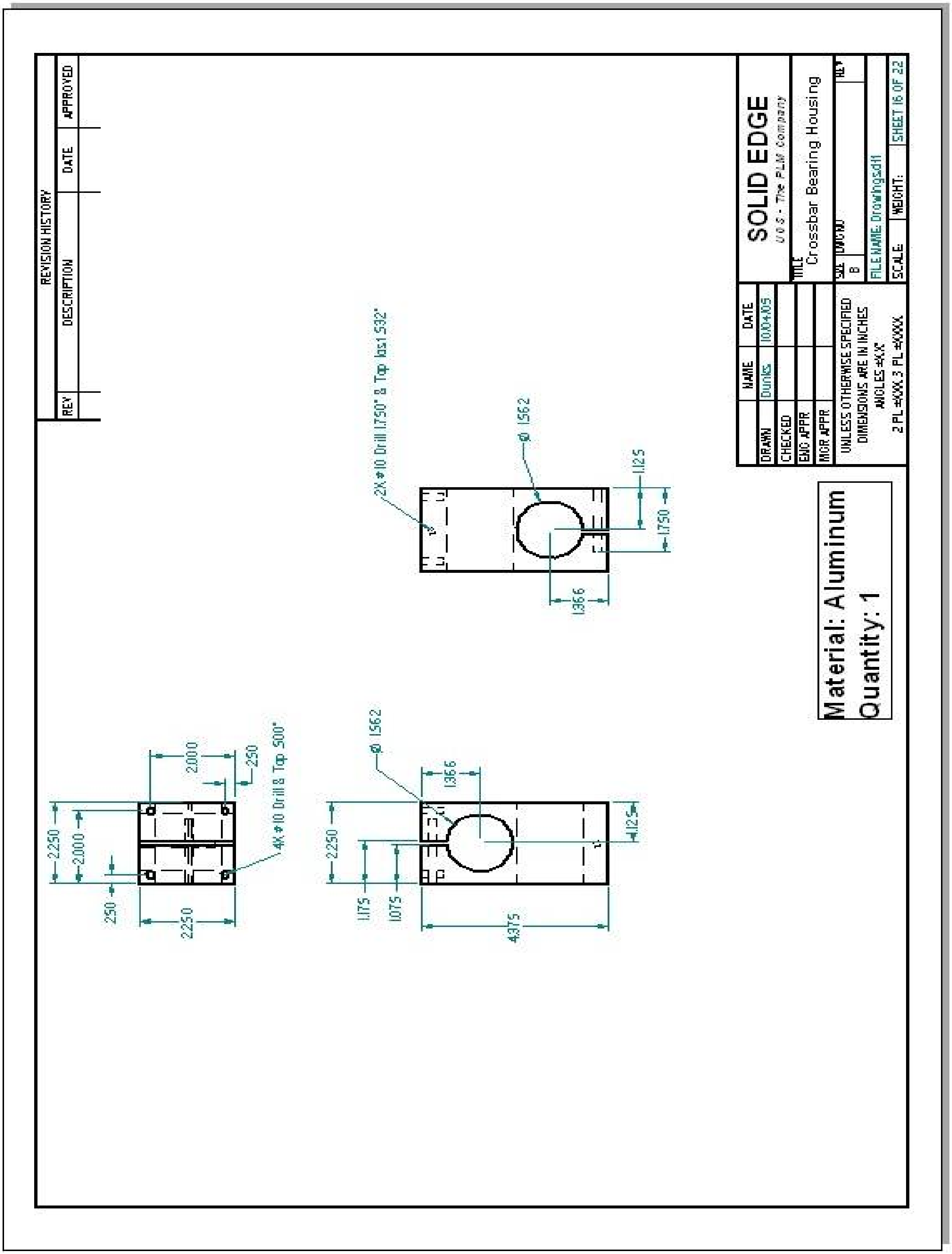

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
4X #10 Drill & Tap .500"
.188
4.250
.875
2X #10 Clearance Thru
Ø 1.125
Ø .875
.750
3.064
6.017
6.767
.188
3.158
4.750
.250
.375
Material: Aluminum
Quantity: 1
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
Corner Support 3a
SIZE
DWG NO
REV
B
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 12 OF 22



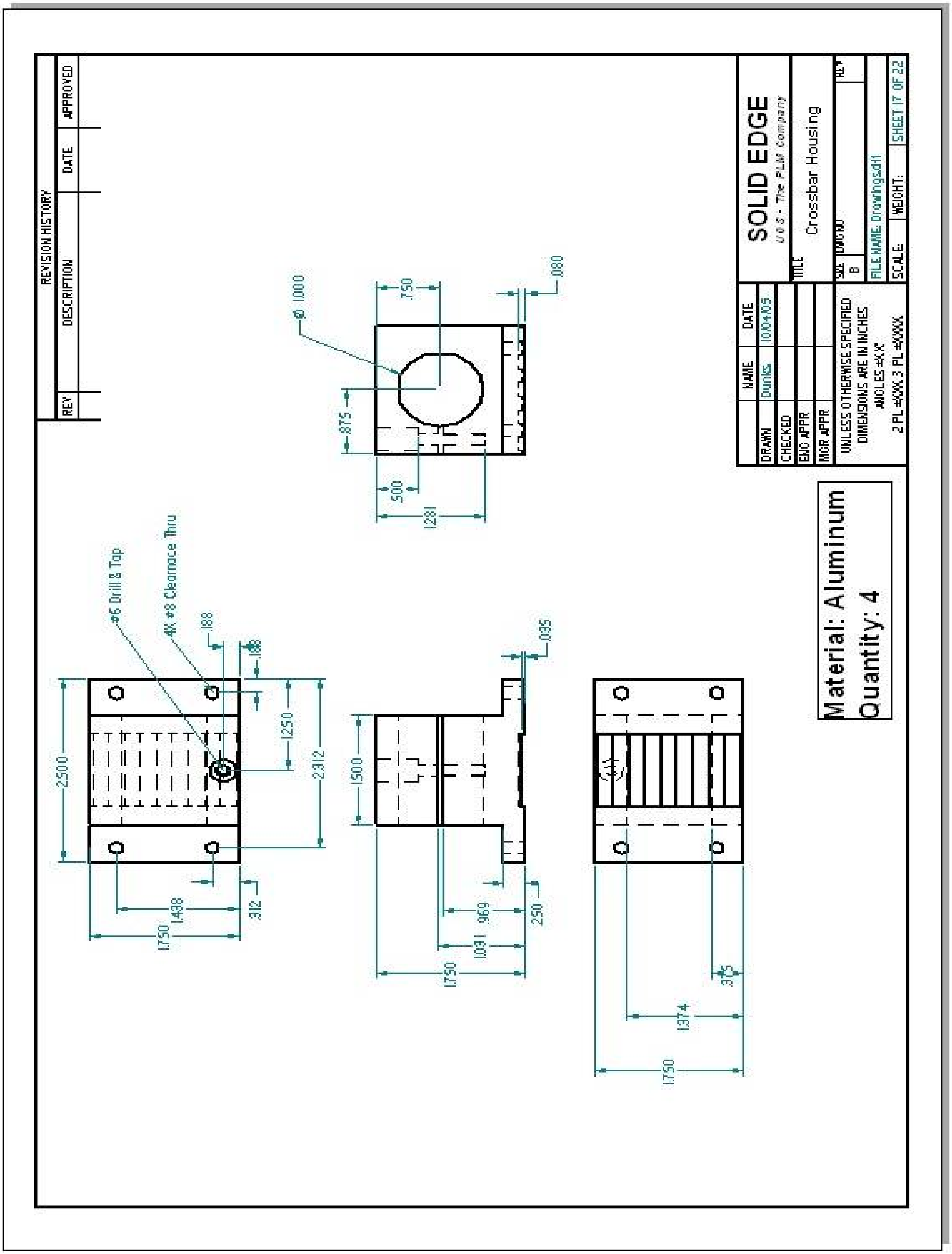
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
6X #10 Drill & Tap .500"
.188
.375
.500
3.250
4X #10 Drill & Tap Thru
Ø 1.125
Ø .875
2.314
3.064
3.814
6.767
1.408
1.908
2.408
2.908
3.750
.250
.750
3.064
6.017
.125
#10 Drill & Tap Thru
Material: Aluminum
Quantity: 1
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
Corner Support 3b
SIZE
B
DWG NO
REV
FILE NAME: Drawings.dft
SCALE:
WEIGHT:
SHEET 13 OF 22


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
SOLID EDGE
UGS - The PLM Company
TITLE
Corner Support 4a
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 14 OF 22
Material: Aluminum
Quantity: 1
4X #10 Drill & Tap .500"
6X #10 Drill & Tap Thru
Ø 1.125
Ø .875
6.017
.750
4.750
4.562
2.635
1.592
.550
2.021
3.064
4.106
6.767
3.875
.500
.188
.375
.250

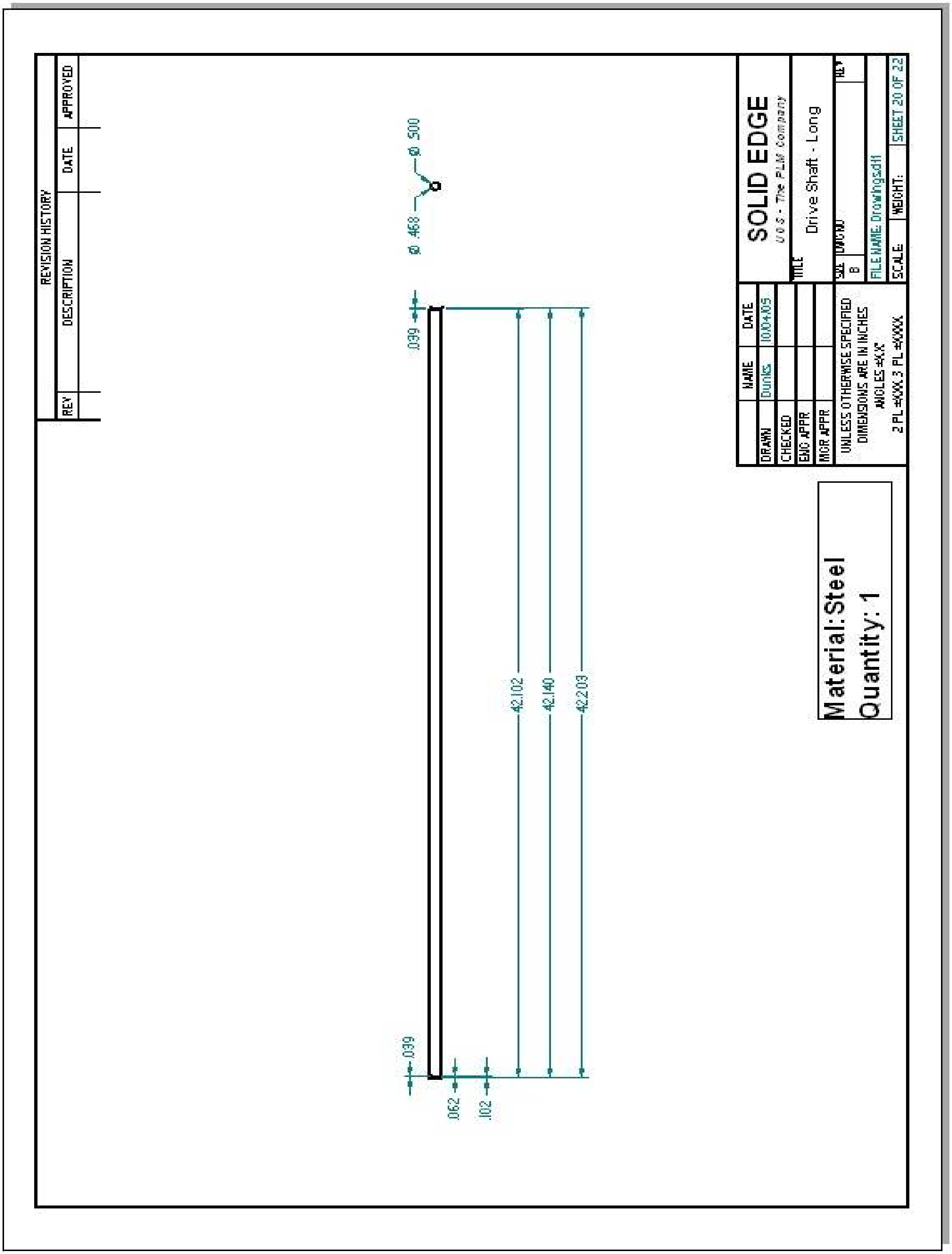

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
6X #10 Drill & Tap .500"
.188
1.125
3.875
Ø 1.125
Ø .875
4X #10 Drill & Tap Thru
2.021
3.064
4.106
6.767
1.115
2.158
3.200
4.375
.250
.188
6.017
.750
.375
Material: Aluminum
Quantity: 1
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
Corner Support 4b
SIZE
B
DWG NO
REV
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 15 OF 22

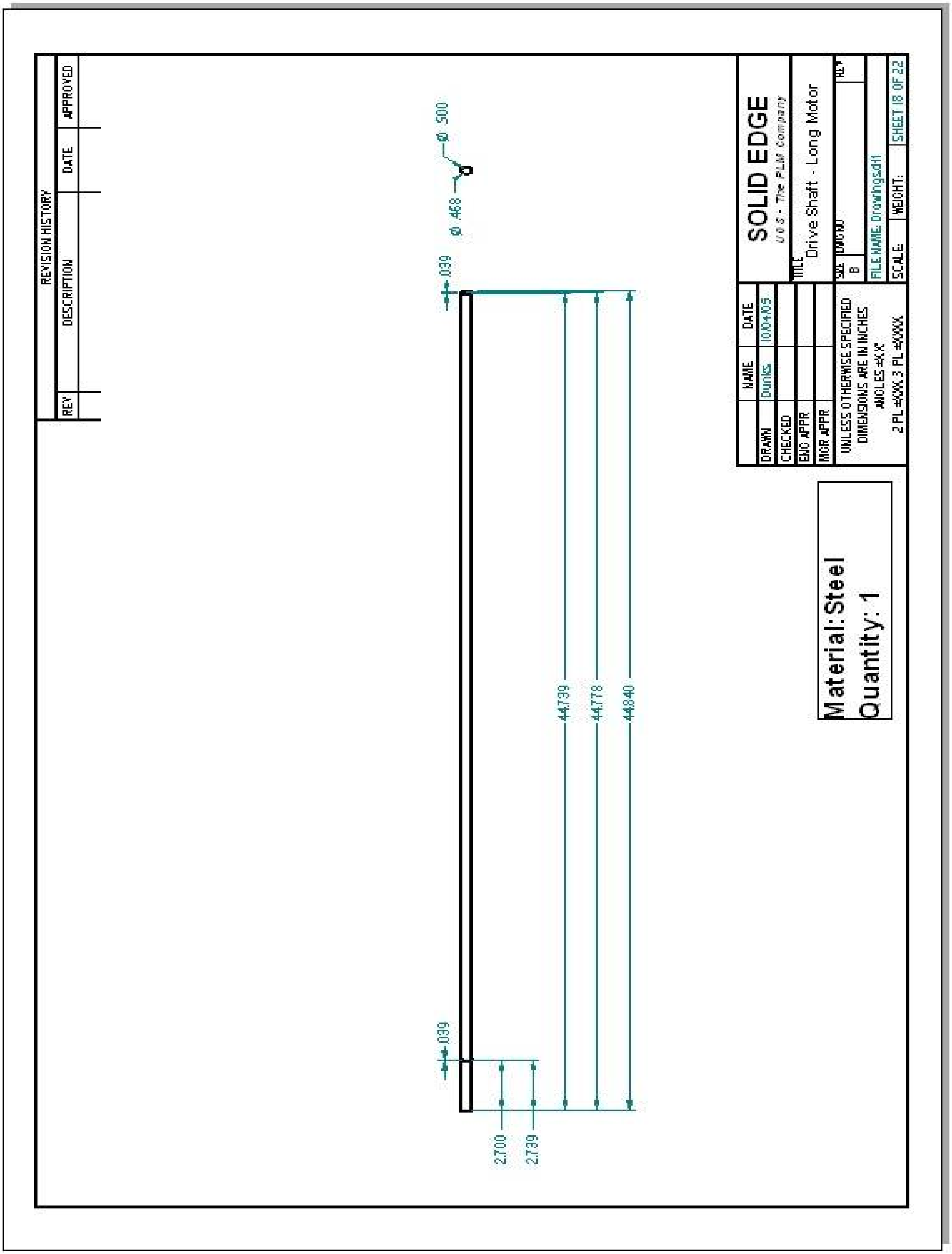


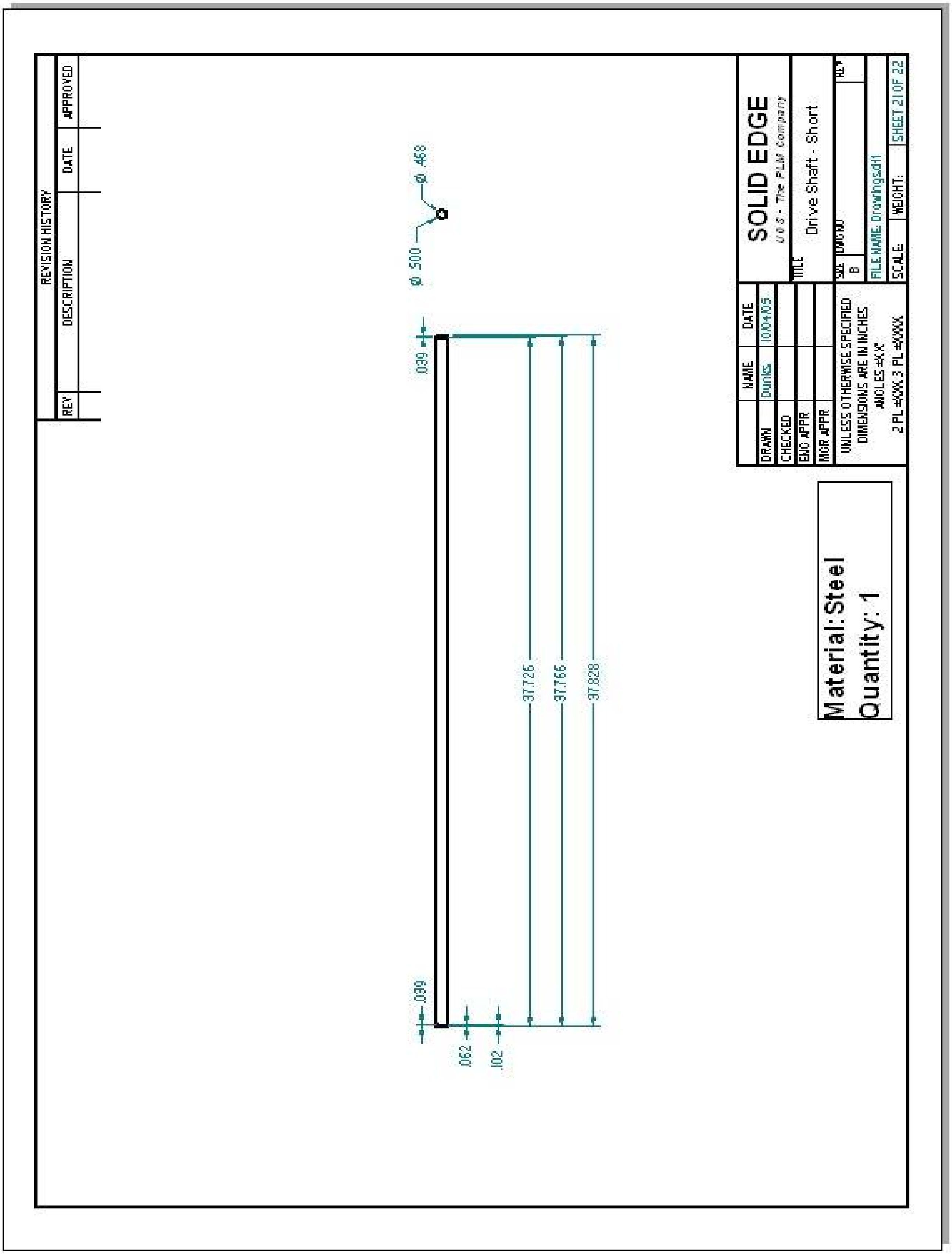
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
SOLID EDGE
UGS - The PLM Company
TITLE
Crossbar Bearing Housing
SIZE
DWG NO
B
REV
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 16 OF 22
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
Material: Aluminum
Quantity: 1
2X #10 Drill 1.750" & Tap las1.532"
Ø 1.562
.125
1.750
1.366
4X #10 Drill & Tap .500"
2.250
2.000
.250
1.175
1.075
4.375

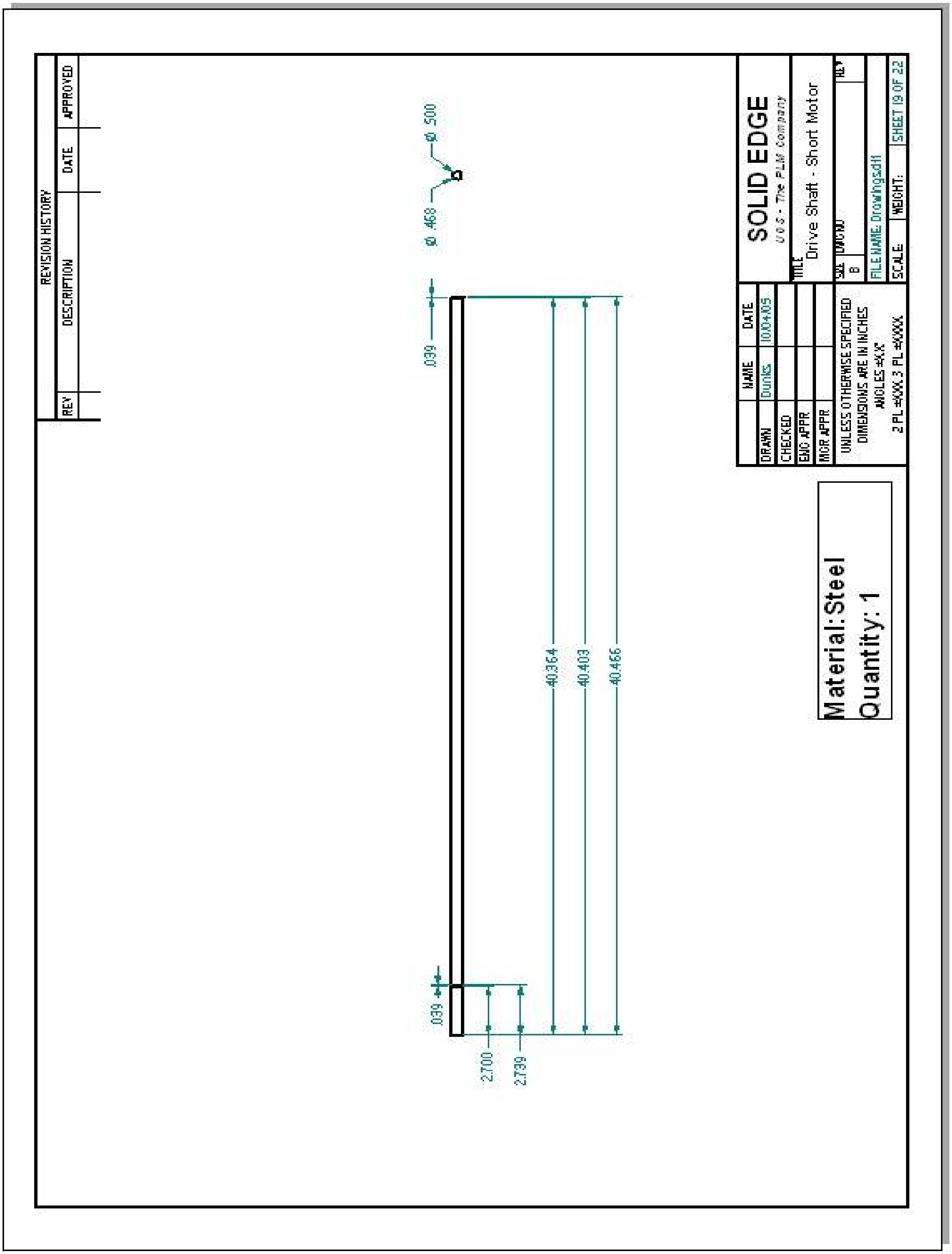


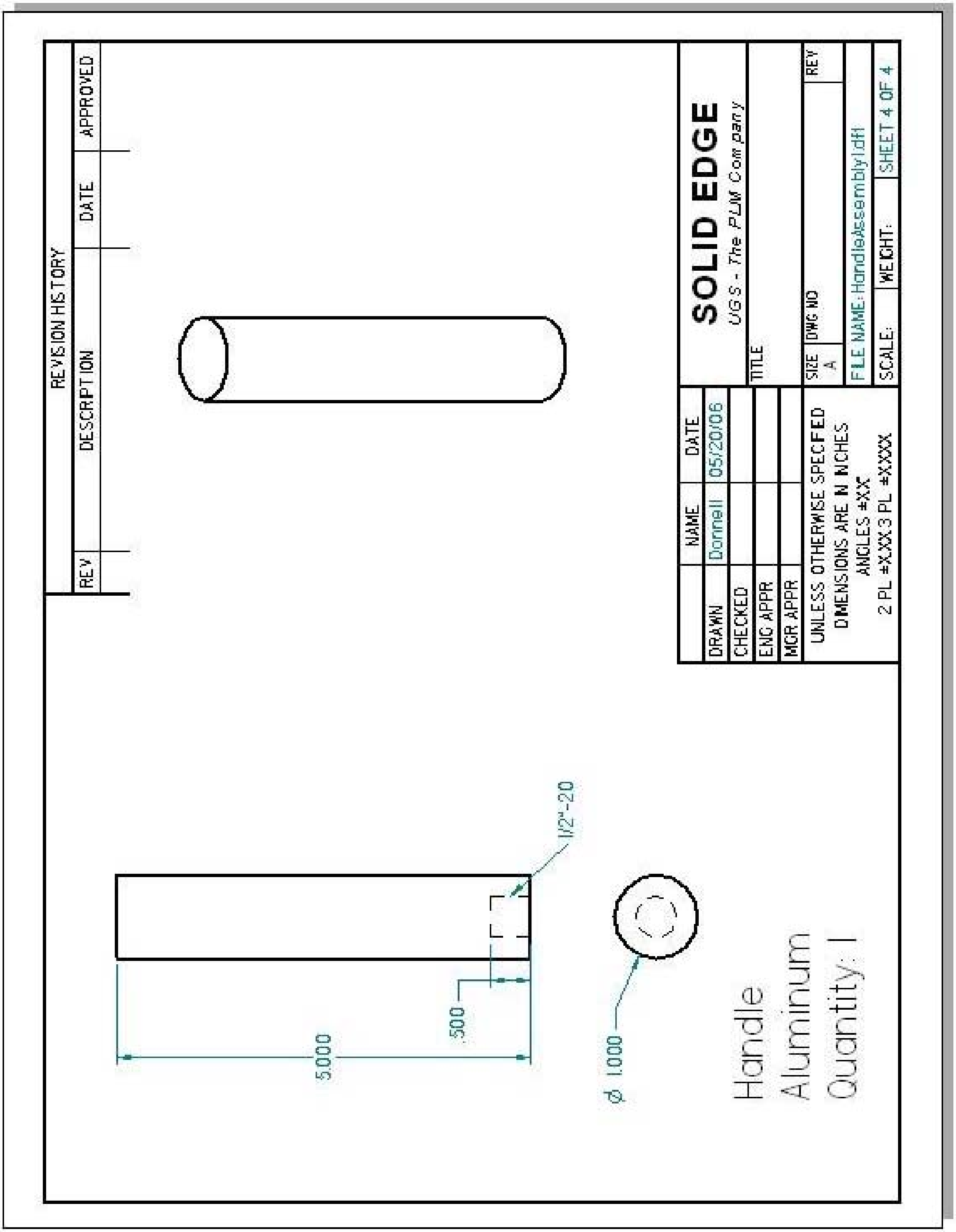
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
SOLID EDGE
UGS - The PLM Company
TITLE
Crossbar Housing
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SIZE
B
DWG NO
REV
FILE NAME: Drawing.sdft
SCALE:
WEIGHT:
SHEET 17 OF 22
Material: Aluminum
Quantity: 4
#6 Drill & Tap
4X #8 Clearnace Thru
Ø 1.000

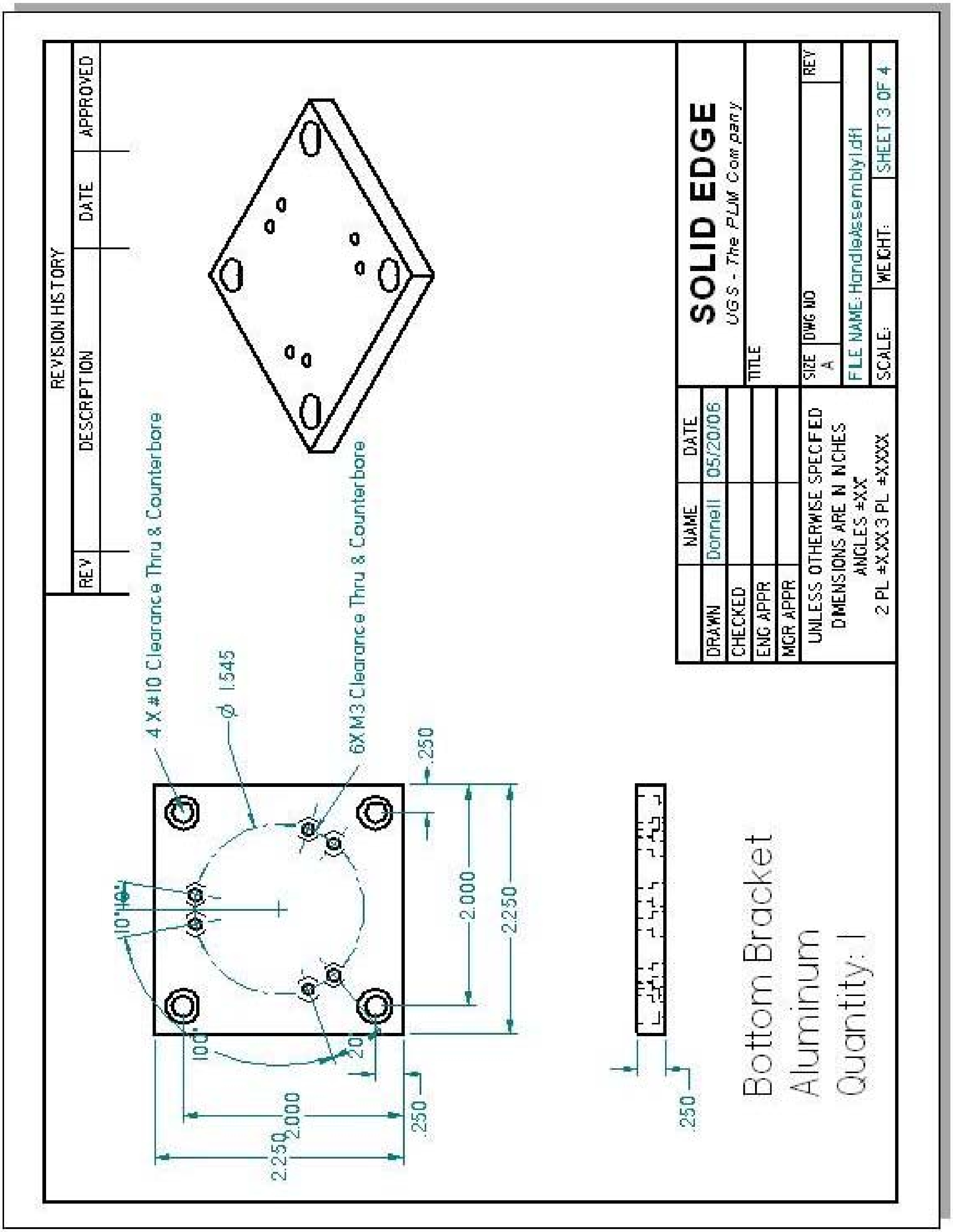

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Ø .468
Ø .500
.039
.039
.062
.102
42.102
42.140
42.203
SOLID EDGE
UGS - The PLM Company
TITLE
Drive Shaft - Long
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SIZE
B
DWG NO
REV
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 20 OF 22
Material: Steel
Quantity: 1

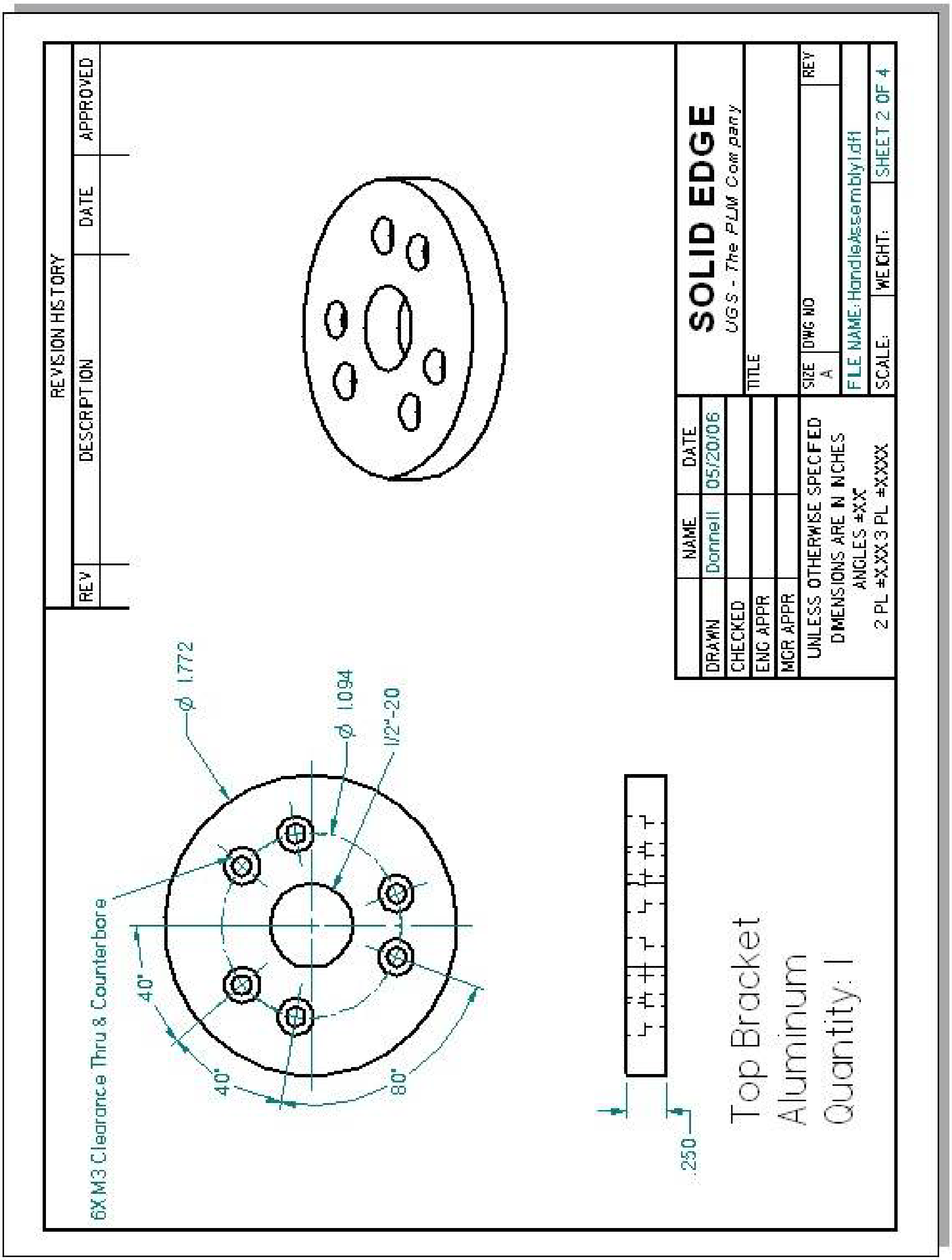

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
.039
Ø .468
Ø .500
.039
2.700
2.739
44.739
44.778
44.840
Material: Steel
Quantity: 1
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
Drive Shaft - Long Motor
SIZE
B
DWG NO
REV
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 18 OF 22

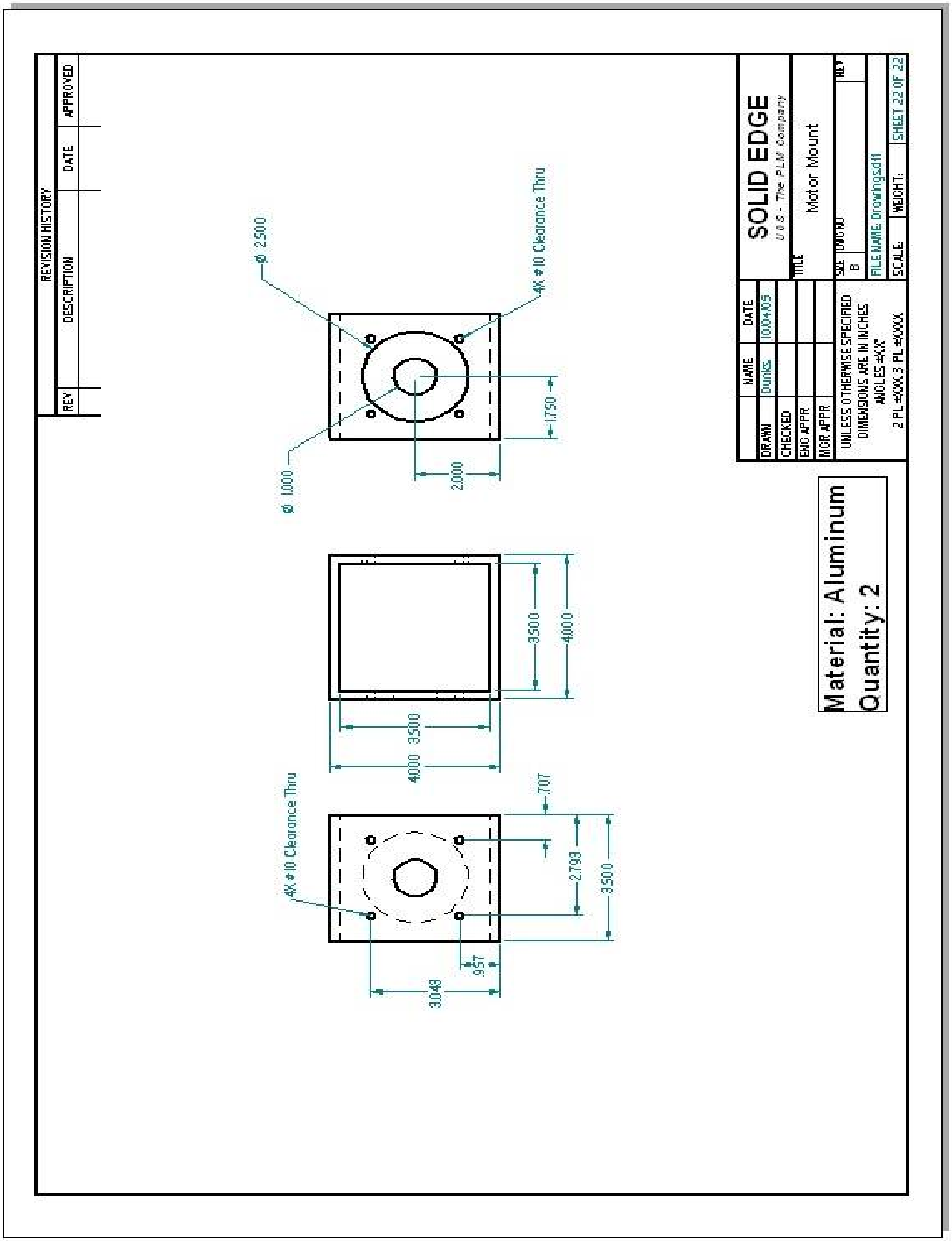

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Ø .500
Ø .468
.039
.039
37.726
37.766
37.828
.062
.102
SOLID EDGE
UGS - The PLM Company
TITLE
Drive Shaft - Short
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
SIZE
B
DWG NO
REV
FILE NAME: Drawingsdft
SCALE:
WEIGHT:
SHEET 21 OF 22
Material: Steel
Quantity: 1


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
.039
.039
Ø .468
Ø .500
2.700
2.739
40.364
40.403
40.466
Material:Steel
Quantity: 1
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
SOLID EDGE
UGS - The PLM Company
TITLE
Drive Shaft - Short Motor
SIZE
B
DWG NO
REV
SCALE:
WEIGHT:
SHEET 19 OF 22

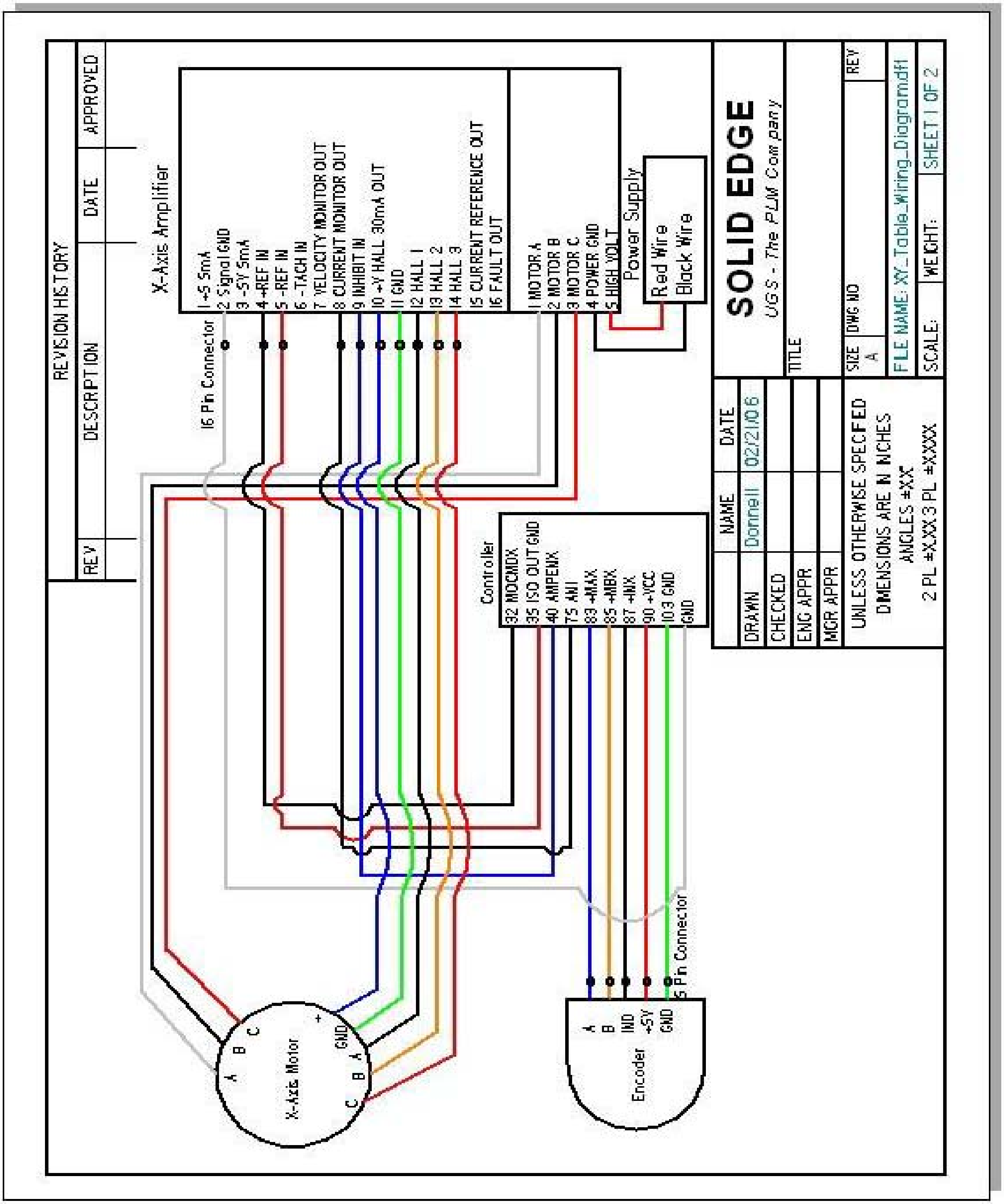

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
1/2"-20
5.000
.500
⌀ 1.000
Handle
Aluminum
Quantity: 1
NAME
DATE
DRAWN
Donnell
05/20/06
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±XX°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
SIZE
A
DWG NO
REV
FILE NAME: HandleAssembly.dft
SCALE:
WEIGHT:
SHEET 4 OF 4

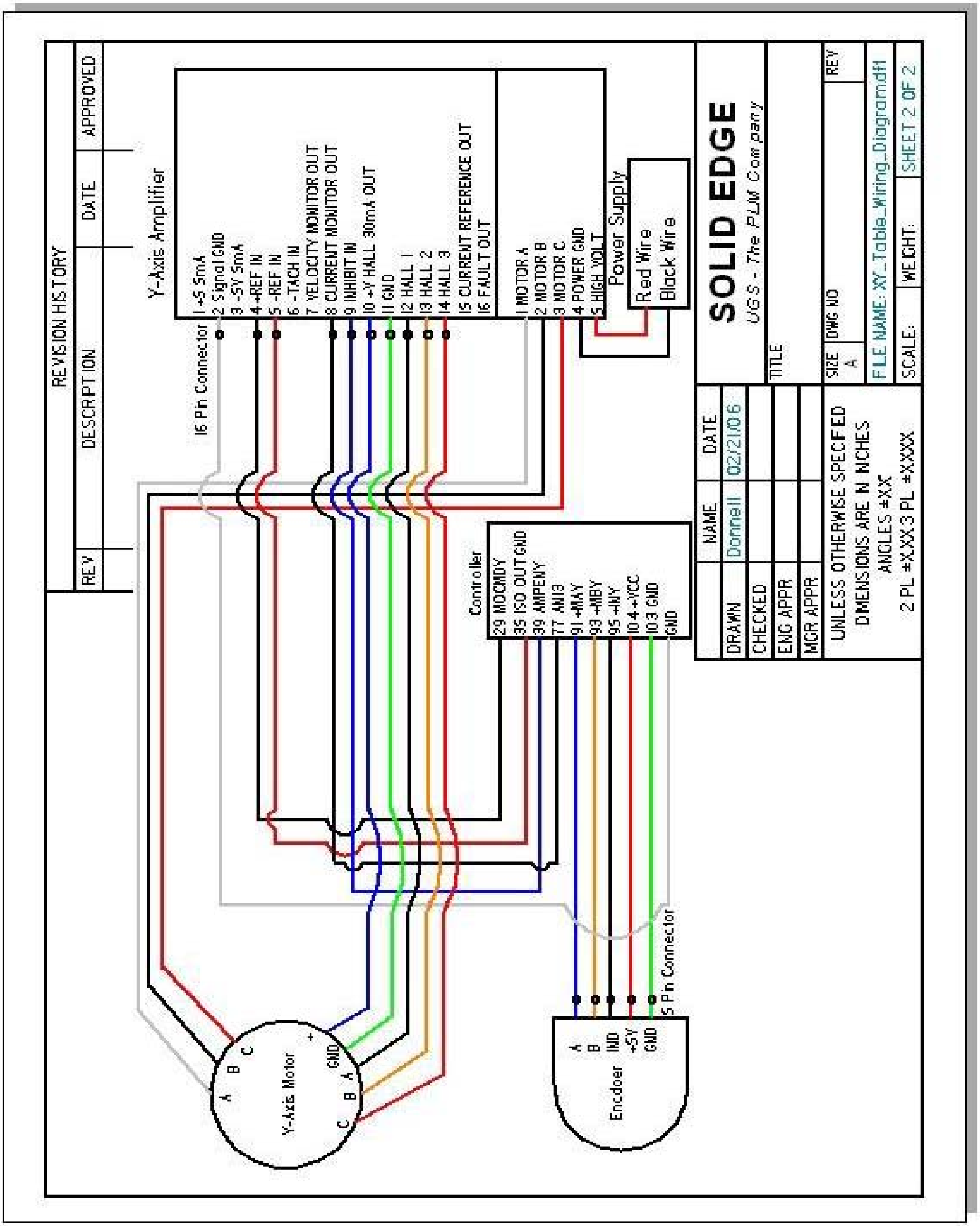

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
4 X #10 Clearance Thru & Counterbore
⌀ 1.545
6X M3 Clearance Thru & Counterbore
10°
10°
100°
20°
.250
2.000
2.250
.250
2.000
2.250
.250
Bottom Bracket
Aluminum
Quantity: 1
NAME
DATE
DRAWN
Donnell
05/20/06
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECFIED
DIMENSIONS ARE IN INCHES
ANGLES ±XX°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
SIZE
A
DWG NO
REV
FILE NAME: HandleAssembly1.dft
SCALE:
WEIGHT:
SHEET 3 OF 4


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
6X M3 Clearance Thru & Counterbore
ø 1.772
ø 1.094
1/2"-20
40°
40°
80°
.250
Top Bracket
Aluminum
Quantity: 1
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
Donnell
05/20/06
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±XX°
2 PL ±X.XX 3 PL ±X.XXX
SOLID EDGE
UGS - The PLM Company
TITLE
SIZE
A
DWG NO
REV
FILE NAME: HandleAssembly1.dft
SCALE:
WEIGHT:
SHEET 2 OF 4


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Ø 2.500
4X #10 Clearance Thru
Ø 1.000
2.000
1.750
3.500
4.000
.707
2.793
.957
3.043
SOLID EDGE
UGS - The PLM Company
Motor Mount
NAME
DATE
DRAWN
Dunks
10/04/05
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TITLE
SIZE
B
FILE NAME: Drawings.dft
SCALE:
WEIGHT:
SHEET 22 OF 22
Material: Aluminum
Quantity: 2

Wiring Diagram





REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Y-Axis Amplifier
1 +5 5mA
2 Signal GND
3 -5V 5mA
4 +REF IN
5 -REF IN
6 -TACH IN
7 VELOCITY MONITOR OUT
8 CURRENT MONITOR OUT
9 INHIBIT IN
10 +V HALL 30mA OUT
11 GND
12 HALL 1
13 HALL 2
14 HALL 3
15 CURRENT REFERENCE OUT
16 FAULT OUT
1 MOTOR A
2 MOTOR B
3 MOTOR C
4 POWER GND
5 HIGH VOLT
16 Pin Connector
Power Supply
Red Wire
Black Wire
Controller
29 MOCMDY
35 ISO OUT GND
39 AMPENY
77 ANI3
91 +MAY
93 +MBY
95 +INY
104 +VCC
103 GND
GND
Y-Axis Motor
A
B
C
+
GND
A
B
C
Encoder
A
B
IND
+5V
GND
5 Pin Connector
SOLID EDGE
UGS - The PLM Company
NAME
DATE
DRAWN
Donnell
02/21/06
CHECKED
ENG APPR
MGR APPR
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
ANGLES ±X.X°
2 PL ±X.XX 3 PL ±X.XXX
TITLE
SIZE
A
DWG NO
REV
FILE NAME: XY_Table_Wiring_Diagram.dft
SCALE:
WEIGHT:
SHEET 2 OF 2

Code

Rectangle

```
#RECT

#HOME
NO BEGINNING OF X HOMEING SEQUENCE
JG -3000
AC 5000
DC 1000
BGX
#HOMEX1
NO FINDS X POSITION LIMIT 1 ON TABLE
TX=_TTX
HCOUNTX=0
IF (@ABS[TX]>2.5)
NO TESTS FOR EXCEEDED TORQUE LIMIT
MG "TX1 TORQUE LIMIT EXCEEDED"
AB 1
NO ABORTS MOTOR MOTION ONLY
MC
DP 0
X1=_TPX
NO DEFINES POSITION X1 ON TABLE
HCOUNTX=1
ENDIF
JP #HOMEX1, HCOUNTX=0

WT 2000

JG 3000
BGX
#HOMEX2

NO FINDS X POSITION LIMIT 2 ON TABLE
TX=_TTX
HCOUNTX=0
IF (@ABS[TX]>2.5)
NO TESTS FOR EXCEEDED TORQUE LIMIT
MG "TX2 TORQUE LIMIT EXCEEDED"
AB 1
NO ABORTS MOTOR MOTION ONLY
MC
X2=_TPX
NO DEFINES POSITION X2 ON TABLE
HCOUNTX=1
ENDIF
JP #HOMEX2, HCOUNTX=0

NO BEGINNING OF Y HOMING SEQUENCE
NO ALL CODE FOR Y HOMING MIRRORS X HOMING EXCEPT IN DIFFERENT AXIS
WT 2000

#HOMEY1
JG ,-3000
```

```
AC ,5000
DC ,1000
BGY
TY=_TTY
HCOUNTY=0
IF (@ABS[TY]>2.5)
MG "TY1 TORQUE LIMIT EXCEEDED"
AB 1
MC
DP ,0
Y1=_TPY
HCOUNTY=1
ENDIF
JP #HOMEY1, HCOUNTY=0

WT 2000
NO CAUSES THE PROGRAM TO WAIT FOR 2 SECONDS

JG ,3000
BGY
#HOMEY2
TY=_TTY
HCOUNTY=0
IF (@ABS[TY]>2.5)
MG "TY2 TORQUE LIMIT EXCEEDED"
AB 1
MC
Y2=_TPY
HCOUNTY=1
ENDIF
JP #HOMEY2, HCOUNTY=0

WT 2000

CON=(7.5/4000)
NO CONVERSION FACTOR CALCULATION
XDIS=X2*CON
YDIS=Y2*CON

MG "ALL USER INPUTS SHOULD BE INPUT IN THE COMMAND WINDOW LOCATED ABOVE"
MG "USERS SHOULD PRESS ENTER FOLLOWING INPUTING DESIRED CONDITIONS"

XSTIN=0
YSTIN=0

#STPOSTN
NO SUBPRGM FOR STARTING POSITION
MG "SPECIFY A STARTING POSITION IN TERMS OF TABLE COORDINATES"
MG "THE X STARTING POSITION MUST BE LESS THAN",XDIS
MG "THE Y STARTING POSITION MUST BE LESS THAN",YDIS
MG "IF POSITIVE NUMERICAL VALUE IS NOT INSERTED SYSTEM WILL DEFAULT TO 0"
IN "INPUT X-AXIS STARTING POSITION IN INCHES",XSTIN
IN "INPUT Y-AXIS STARTING POSITION IN INCHES",YSTIN

#PCHECK
NO SUBPRGM TO CHECK TO MAKE SURE STARTING POSITION IS WITHIN TABLE LIMITS
CHECK=0
```

```
IF (XSTIN>XDIS)|(YSTIN>YDIS)
NO TABLE LIMITS CHECK
XSTIN=0
YSTIN=0
MG "CHOSEN STARTING POSITION LIES OUTSIDE OF TABLE WORKSPACE"
IN "INPUT X-AXIS STARTING POSITION IN INCHES",XSTIN
IN "INPUT Y-AXIS STARTING POSITION IN INCHES",YSTIN
CHECK=1
ENDIF
JP #PCHECK, CHECK=1

IF (XSTIN<0)
XSTIN=0
ENDIF

IF (YSTIN<0)
YSTIN=0
ENDIF

MG "THE DESIRED X-AXIS STARTING POSITION IS",XSTIN
MG "THE DESIRED Y-AXIS STARTING POSITION IS",YSTIN
NO MESSAGES THE DESIRED STARTING POSITIONS

XSTCO=XSTIN/CON
YSTCO=YSTIN/CON

#STMOVE
NO SUBPRGM TO START MOVE
PA XSTCO,YSTCO
NO MOVES TO STARTING POSITION
SP 3000,3000
NO DEFINES MOVEMENT SPEED
AC 5000,5000
NO DEFINES ACCELERATION
DC 1000,1000
NO DEFINES DECELERATION
BGXY
NO BEGIN MOTION IN BOTH X AND Y AXIS
AM XY

#RECDIM
NO SUBPRGM FOR SELECTING DESIRED RECTANGULAR DIMENSIONS
XMAX=X2-XSTCO
XMAX=XMAX*CON
NO CALCULATES MAXIMUM ALLOWABLE X-AXIS DISTANCE
YMAX=Y2-YSTCO
YMAX=YMAX*CON
NO CALCULATES MAXIMUM ALLOWABLE Y-AXIS DISTANCE
MG "SPECIFY THE DIMENSIONS OF YOUR RECTANGLE"
MG "THE X-AXIS DIMENSION MUST BE LESS THAN",XMAX
MG "THE Y-AXIS DIMENSION MUST BE LESS THAN",YMAX
MG "IF POSITIVE NUMERICAL VALUE IS NOT INSERTED SYSTEM WILL DEFAULT TO 0"
IN "INPUT DESIRED X-AXIS DIMENSION IN INCHES",XDIMIN
IN "INPUT DESIRED Y-AXIS DIMENSION IN INCHES",YDIMIN

#DMCHECK
NO SUBPRGM CHECKING TO SEE IF RECTANGULAR DIMENSIONS LIE WITHIN WORKSPACE
```

```
CHECK=0
IF (XDIMIN>XMAX)|(YDIMIN>YMAX)
MG "CHOSEN RECTANGLE DIMENSIONS ARE TOO LARGE"
IN "INPUT DESIRED X-AXIS DIMENSION IN INCHES",XDIMIN
IN "INPUT DESIRED Y-AXIS DIMENSION IN INCHES",YDIMIN
CHECK=1
ENDIF
JP #DMCHECK, CHECK=1
NO LOOKS DMCHECK UNTIL CONDITIONS ARE SATISFIED

IF (XDIMIN<0)
XDIMIN=0
ENDIF

IF (YDIMIN<0)
YDIMIN=0
ENDIF

#RECMOVE
WT 2000
NO RECTANGLE MOVEMENT SUBPRGM
SP 10000,10000
AC 5000,5000
DC 1000,1000
PR (XDIMIN/CON),(YDIMIN/CON)
NO DEFINES RECT RELATIVE POSITION MOVE
BG X

WT 2000

#TLIMIT1
NO LOOP TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=2.5)|(@ABS[_TTY]>=2.5)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #TLIMIT1, COUNT=0

BG Y
#TLIMIT2
NO TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF
```

```
IF (@ABS[_TTX]>=2.5)|(@ABS[_TTY]>=2.5)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #TLIMIT2, COUNT=0

AM
NO MOVES TABLE TO X2 POSITION, FOLLOWED BY Y2 POSITION
NO AFTER THE COMPLETEION OF X2 MOVE

PR (-XDIMIN/CON),(-YDIMIN/CON)
NO DEFINES RECT RELATIVE POSITION MOVE
BG X
#TLIMIT3
COUNT=0
IF(_BGX=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=2.5)|(@ABS[_TTY]>=2.5)
MG "TORQUE LIMIT EXCEEDED"
AB 0
COUNT=1
ENDIF
JP #TLIMIT3, COUNT=0


AM X
BG Y
NO MOVES TABLE TO X1 POSITION, FOLLOWED BY Y1 POSITION
NO AFTER THE COMPLETEION OF X1 MOVE
#TLIMIT4
COUNT=0
IF(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=2.5)|(@ABS[_TTY]>=2.5)
MG "TORQUE LIMIT EXCEEDED"
AB 0
COUNT=1
ENDIF
JP #TLIMIT4, COUNT=0


AM Y

#RERUN
IN "WOULD YOU LIKE TO RUN THE PROGRAM AGAIN? 1 FOR YES, 2 FOR NO",REPEAT
NO PROMPS TO SEE IF USER WANTS TO RUN PROGRAM AGAIN
IF (REPEAT<>1)&(REPEAT<>2)
```

```
MG "INVALID SELECTION"
NO TESTS TO ENSURE USER SELECTED VALID CHOICE
JP #RERUN
ENDIF
JP #STPOSTN, REPEAT=1
JP #END, REPEAT=2

#END
MG "PROGRAM ENDING NOW"
EN
```

Rectangle / Circle

```
#BC
NO DEFINING CONSTANTS
TLIM=5

#HOME
NO BEGINNING OF X HOMEING SEQUENCE
JG -3000
AC 5000
DC 1000
BGX
#HOMEX1
NO FINDS X POSITION LIMIT 1 ON TABLE
TX=_TTX
HCOUNTX=0
IF (@ABS[TX]>1.5)
NO TESTS FOR EXCEEDED TORQUE LIMIT
MG "TX1 TORQUE LIMIT EXCEEDED"
AB 1
NO ABORTS MOTOR MOTION ONLY
MC
DP 0
X1=_TPX
NO DEFINES POSITION X1 ON TABLE
HCOUNTX=1
ENDIF
JP #HOMEX1, HCOUNTX=0

WT 2000

JG 3000
BGX
#HOMEX2
NO FINDS X POSITION LIMIT 2 ON TABLE
TX=_TTX
HCOUNTX=0
IF (@ABS[TX]>1.5)
NO TESTS FOR EXCEEDED TORQUE LIMIT
MG "TX2 TORQUE LIMIT EXCEEDED"
AB 1
NO ABORTS MOTOR MOTION ONLY
MC
X2=_TPX
NO DEFINES POSITION X2 ON TABLE
```

```
HCOUNTX=1
ENDIF
JP #HOMEX2, HCOUNTX=0

NO BEGINNING OF Y HOMING SEQUENCE
NO ALL CODE FOR Y HOMING MIRRORS X HOMING EXCEPT IN DIFFERENT AXIS
WT 2000

#HOMEY1
JG ,-3000
AC ,5000
DC ,1000
BGY
TY=_TTY
HCOUNTY=0
IF (@ABS[TY]>3)
MG "TY1 TORQUE LIMIT EXCEEDED"
AB 1
MC
DP ,0
Y1=_TPY
HCOUNTY=1
ENDIF
JP #HOMEY1, HCOUNTY=0

WT 2000

JG ,3000
BGY
#HOMEY2
TY=_TTY
HCOUNTY=0
IF (@ABS[TY]>3)
MG "TY2 TORQUE LIMIT EXCEEDED"
AB 1
MC
Y2=_TPY
HCOUNTY=1
ENDIF
JP #HOMEY2, HCOUNTY=0

WT 2000

MG "ALL USER INPUTS SHOULD BE INPUT IN THE COMMAND WINDOW LOCATED ABOVE"
MG "USERS SHOULD PRESS ENTER FOLLOWING INPUTING DESIRED CONDITIONS"

NO PROMPS THE USER ON WHICH PROGRAM THEY WOULD LIKE TO EXECUTE
MG "YOU HAVE LOADED THE BOX OR CIRCLE PROGRAM"

#PGCH
NO PROGRAM CHOICE JUMP LOCATION
IN "TYPE 1 FOR BOX, TYPE 2 FOR CIRCLE",PRGM

#CHECK
CNT=0
IF (PRGM<>1)&(PRGM<>2)
MG "INVALID SELECTION, INPUT MUST BE EITHER 1 OR 2"
```

```
IN "TYPE 1 FOR BOX, TYPE 2 FOR CIRCLE",PRGM
CNT=1
ENDIF
JP #CHECK, CNT=1

JP #BOX, PRGM=1
JP #CIRCLE, PRGM=2

NO BEGIN OF CIRCLE SEQUENCE
#CIRCLE
PA (X2/2)+(Y2/3),Y2/2
NO POSITIONS TABLE FOR START OF CIRCLE
BG

AM

VM XY
NO SPECIFY AXES FOR VECTOR COORDINATED MOTION
VS 5000
NO DEFINES VECTOR SPEED
VA 5000
NO DEFINES VECTOR ACCELERATION
VD 1000
NO DEFINES VECTOR DECELERATION
CR Y2/8,0,360
NO DEFINES A CIRCLE OF RADIUS Y2/3
NO CIRCLE IS TO START AT 0 DEGREE MARK AND GO TO 360 DEGREE
VE
NO END OF VECTOR SEQUENCE
BGS
NO BEGIN SEQUENCE

#BOUNDS
NO TESTS TO ENSURE THAT TABLE STAYS WITHIN PHYSICAL LIMITS
COUNT=0
IF(_BG=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
MG "MOTION COMPLETE"
COUNT=1
ENDIF

IF (_TPX<=X1)|(_TPX>=X2)|(_TPY<=Y1)|(_TPY>=Y2)
NO CONTINUALLY CHECKS TO MAKE SURE TABLE IS WITHIN PHYSICAL LIMITS
MG "SYSTEM EXCEEDED BOUNDS"
AB 1
NO IF SYSTEM IS OUTSIDE LIMITS AND MOTION IS ABORTED
COUNT=1
ENDIF

NO LOOP TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)&(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF
```

```
IF (@ABS[_TTX]>=TLIM)|(@ABS[_TTY]>=TLIM)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #BOUNDS, COUNT=0

IN "WOULD YOU LIKE TO RUN THE PROGRAM AGAIN? 1 FOR YES, 2 FOR NO",REPEAT
NO PROMPS TO SEE IF USER WANTS TO RUN ANOTHER PROGRAM
#REPEAT1
RCNT=0
IF (REPEAT<>1)&(REPEAT<>2)
MG "INVALID SELECTION"
IN "IN "WOULD YOU LIKE TO RUN THE PROGRAM AGAIN? 1 FOR YES, 2 FOR NO",REPEAT
RCNT=1
ENDIF
JP #REPEAT1, RCNT=1

JP #PGCH, REPEAT=1
JP #END, REPEAT=2

NO BEGINNING OF BOX SEQUENCE
#BOX
WT 2000
PA X1,Y1
SP 10000,10000
AC 5000,5000
DC 700,700
BG

NO MOVES TABLE TO START POSITION

AM

PA X2,Y2
BG X
#TLIM1
NO LOOP TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)&(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=TLIM)|(@ABS[_TTY]>=TLIM)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #TLIM1, COUNT=0

AM X
```

```
BG Y

#TLIM2
NO LOOP TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)&(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=TLIM)|(@ABS[_TTY]>=TLIM)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #TLIM2, COUNT=0
AM
NO MOVES TABLE TO X2 POSITION, FOLLOWED BY Y2 POSITION
NO AFTER THE COMPLETEION OF X2 MOVE

PA X1,Y1
BG X
#TLIM3
NO LOOP TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)&(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=TLIM)|(@ABS[_TTY]>=TLIM)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #TLIM3, COUNT=0
AM X
BG Y
#TLIM4
NO LOOP TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)&(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=TLIM)|(@ABS[_TTY]>=TLIM)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
```

```
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #TLIM4, COUNT=0
NO MOVES TABLE TO X1 POSITION, FOLLOWED BY Y1 POSITION
NO AFTER THE COMPLETEION OF X1 MOVE
AM
IN "WOULD YOU LIKE TO RUN THE PROGRAM AGAIN? 1 FOR YES, 2 FOR NO",REPEAT
NO PROMPS TO SEE IF USER WANTS TO RUN ANOTHER PROGRAM
#REPEAT2
RCNT=0
IF (REPEAT<>1)&(REPEAT<>2)
MG "INVALID SELECTION"
IN "IN "WOULD YOU LIKE TO RUN THE PROGRAM AGAIN? 1 FOR YES, 2 FOR NO",REPEAT
RCNT=1
ENDIF
JP #REPEAT2, RCNT=1

JP #PGCH, REPEAT=1
JP #END, REPEAT=2

#END
MG "EXITING PROGRAM NOW"
```

Reach

```
#REACH

NO DEFINING CONSTANTS
TLIM=5

#HOME
NO BEGINNING OF X HOMEING SEQUENCE
JG -3000
AC 5000
DC 1000
BGX
#HOMEX1
NO FINDS X POSITION LIMIT 1 ON TABLE
TX=_TTX
HCOUNTX=0
IF (@ABS[TX]>2.5)
NO TESTS FOR EXCEEDED TORQUE LIMIT
MG "TX1 TORQUE LIMIT EXCEEDED"
AB 1
NO ABORTS MOTOR MOTION ONLY
MC
DP 0
X1=_TPX
NO DEFINES POSITION X1 ON TABLE
HCOUNTX=1
ENDIF
JP #HOMEX1, HCOUNTX=0

WT 2000
```

```
JG 3000
BGX
#HOMEX2
NO FINDS X POSITION LIMIT 2 ON TABLE
TX=_TTX
HCOUNTX=0
IF (@ABS[TX]>2.5)
NO TESTS FOR EXCEEDED TORQUE LIMIT
MG "TX2 TORQUE LIMIT EXCEEDED"
AB 1
NO ABORTS MOTOR MOTION ONLY
MC
X2=_TPX
NO DEFINES POSITION X2 ON TABLE
HCOUNTX=1
ENDIF
JP #HOMEX2, HCOUNTX=0

NO BEGINNING OF Y HOMING SEQUENCE
NO ALL CODE FOR Y HOMING MIRRORS X HOMING EXCEPT IN DIFFERENT AXIS
WT 2000

#HOMEY1
JG ,-3000
AC ,5000
DC ,1000
BGY
TY=_TTY
HCOUNTY=0
IF (@ABS[TY]>2.5)
MG "TY1 TORQUE LIMIT EXCEEDED"
AB 1
MC
DP ,0
Y1=_TPY
HCOUNTY=1
ENDIF
JP #HOMEY1, HCOUNTY=0

WT 2000

JG ,3000
BGY
#HOMEY2
TY=_TTY
HCOUNTY=0
IF (@ABS[TY]>2.5)
MG "TY2 TORQUE LIMIT EXCEEDED"
AB 1
MC
Y2=_TPY
HCOUNTY=1
ENDIF
JP #HOMEY2, HCOUNTY=0

WT 2000
```

```
MG "ALL USER INPUTS SHOULD BE INPUT IN THE COMMAND WINDOW LOCATED ABOVE"
MG "USERS SHOULD PRESS ENTER FOLLOWING INPUTING DESIRED CONDITIONS"

#PGRM
NO BEGINNING OF ACTUAL REACHING PROGRAM
PA (X2/2),Y2
NO MOVES TABLE TO DESIRED STARTING POSITION
BG

#TLIMIT1
NO LOOP TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)&(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=TLIM)|(@ABS[_TTY]>=TLIM)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #TLIMIT1, COUNT=0

AM

MG "THETA MUST BE BETWEEN 0 AND 90 DEGREES"
MG "IF NEGATIVE VALUE IS INPUT ABSOLUTE VALUE WILL BE USED"
IN "INPUT YOUR DESIRED ANGULAR POSITION CHANGE IN DEGREES",THETA
THETA=@ABS[THETA]

NO USER INPUTS DESIRED ANGULAR POSITION CHANGE
#THTEST
NO LOOP TESTS TO SEE IF THETA IS BETWEEN 0 & 90
TESTCNT=0
IF (THETA>90)|(THETA<0)
MG "CHOSEN THETA OUTSIDE OF LIMITS"
MG "THETA MUST BE BETWEEN 0 AND 90 DEGREES"
IN "INPUT YOU DESIRED ANGULAR POSITION CHANGE IN DEGREES",THETA
NO INPUTS NEW USER THETA
TESTCNT=1
ENDIF
JP #THTEST, TESTCNT=1
MG "WOULD YOU LIKE TO MOVE TO THE LEFT OR TO THE RIGHT OF THE VERTICAL"
IN "1 FOR LEFT OR 2 FOR RIGHT",LR
NO USER INPUTS WOULD THEY LIKE TO MOVE TO THE LEFT OR RIGHT OF VERTICAL
#LRTEST
NO LOOP TESTS TO SEE IF 1 OR 2 IS CHOSEN FOR DIRECTION
TESTLR=0
IF (LR<>1)&(LR<>2)
MG "INVALID CHOICE"
IN "1 FOR LEFT OR 2 FOR RIGHT",LR
NO INPUTS NEW USER LR
TESTLR=1
```

```
ENDIF
JP #LRTEST, TESTLR=1
MG "THETA IS",THETA
MG "LR IS",LR

#REA

LM XY
NO SETS PROGRAM INTO LINEAR INTERPOLATION MODE
R=(Y2/2)
NO DEFINES REACHING RADIUS
IF (LR=1)
NO TESTS TO SEE IF USER DESIRED TO MOVE LEFT OF VERTICAL
XX=-R*@SIN[THETA]
YY=-R*@COS[THETA]
NO COMPUTES NECESSARY X AND Y COORDINATES
ELSE
NO TESTS TO SEE IF USER DESIRED TO MOVE RIGHT OF VERTICAL
XX=R*@SIN[THETA]
YY=-R*@COS[THETA]
NO COMPUTES NECESSARY X AND Y COORDINATES
ENDIF
VS 5000
NO DEFINES VECTOR SPEED
VA 5000
NO DEFINES VECTOR ACCELERATION
VD 1000
NO DEFINES VECTOR DECELERATION
LI XX,YY
NO SPECIFIES LINEAR SEGMENT TO BE TRAVELED
LE
NO END OF LINEAR SEGMENT
BGS
NO BEGINS MOTION
#BOUNDS1
NO TESTS TO ENSURE THAT TABLE STAYS WITHIN PHYSICAL LIMITS
COUNT=0
IF(_BG=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (_TPX<=X1)|(_TPX>=X2)|(_TPY<=Y1)|(_TPY>=Y2)
NO CONTINUALLY CHECKS TO MAKE SURE TABLE IS WITHIN PHYSICAL LIMITS
MG "SYSTEM EXCEEDED BOUNDS"
AB 0
NO IF SYSTEM IS OUTSIDE LIMITS AND MOTION IS ABORTED
COUNT=1
ENDIF

NO LOOP TESTS TO ENSURE THAT TORQUE LIMIT IS NOT EXCEEDED
COUNT=0
NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)&(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF
```

```
IF (@ABS[_TTX]>=TLIM)|(@ABS[_TTY]>=TLIM)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF
JP #BOUNDS1, COUNT=0

AM

LM XY
LI -XX,-YY
LE
BGS

#BOUNDS2
NO TESTS TO ENSURE THAT TABLE STAYS WITHIN PHYSICAL LIMITS
COUNT=0
IF(_BG=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (_TPX<=X1)|(_TPX>=X2)|(_TPY<=Y1)|(_TPY>=Y2)
NO CONTINUALLY CHECKS TO MAKE SURE TABLE IS WITHIN PHYSICAL LIMITS
MG "SYSTEM EXCEEDED BOUNDS"
AB 0
NO IF SYSTEM IS OUTSIDE LIMITS AND MOTION IS ABORTED
COUNT=1
ENDIF

NO STATEMENT CHECKS TO MAKE SURE MOTION IS NOT COMPLETE
IF(_BGX=0)&(_BGY=0)
NO RETURNS 1 IF TABLE STILL IN MOTION, 0 IF MOTION IS COMPLETE
COUNT=1
ENDIF

IF (@ABS[_TTX]>=TLIM)|(@ABS[_TTY]>=TLIM)
NO CONTINUALLY CHECKS TO MAKE SURE TORQUE LIMIT IS NOT EXCEEDED
MG "TORQUE LIMIT EXCEEDED"
AB 0
NO IF TORQUE LIMIT IS EXCEEDED MOTION IS ABORTED
COUNT=1
ENDIF

JP #BOUNDS2, COUNT=0

AM
IN "WOULD YOU LIKE TO RUN THE PROGRAM AGAIN? 1 FOR YES, 2 FOR NO",REPEAT

JP #PGRM, REPEAT=1
JP #END, REPEAT=2

#END
MG "EXITING PROGRAM"
```

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